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Predicting N mineralized in a Georgia Coastal Plain field

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Abstract

The N mineralized from soil organic matter provides an important portion of N available for crop production. The objective of this study was to determine the amount of spatial variability in N mineralization potential in a field and to evaluate three different methods that might be used to estimate this variability. The three methods tested included predicting the N mineralized from surface soil properties as well as from a biological and a chemical procedure. Three soils varying in N mineralization potential were selected for the study from a field in the Georgia Coastal Plain. The N mineralized from these soils was determined by an N balance of unfertilized and cropped plots. The amount of N mineralized could not be reliably predicted from surface soil organic C, although surface soil clay concentration was positively correlated with the N mineralized. The N mineralized that was predicted using mineralization parameters determined by aerobic incubation, adjusted daily for soil water content and temperature, was approximately 50% of the field measurements of N mineralized. The values of NH_4-N extracted with hot 2 *M* KCl were related significantly to N mineralized in the field ($r^2 = 0.60$) and also to the zero order rate constant of mineralization, k_0 ($r^2 = 0.77$), determined from the N mineralized in the aerobic laboratory incubation.

Introduction

Many fields in the Coastal Plain region of the southern USA have soils with widely different physical and chemical properties. Uniform application of N fertilizer to these fields can result in excessive N in some field areas and inadequate N in others. Excessive N applications not only increase expenses for the farmer, but may also contaminate groundwater with NO_3-N, and increase the acidification of the soil unnecessarily. Insufficient N availability, however, limits crop yield and economic return to the farmer. Therefore, the spatial variability within the field should be considered when applying N fertilizer.

One basis for determining the amount of N fertilizer needed is to estimate the total N required by the crop from the expected yield, and then to subtract the other sources of N in the soil that will be available to the crop (Neeteson 1990). The expected yield depends on the yield potential of the soil/climate and can, where applicable, be corrected for stored soil water (Kissel et al. 1975). The N available from the soil depends on the initial available N concentration in the soil, the amount of N mineralized from crop residues, manure, and soil organic matter, the N added to the soil by rain, and N losses through leaching, denitrification, and ammonia volatilization. Because the sources of available N vary with soil properties and landscape position, the sum of available N will also vary across the field.

Except for the initial N concentration in the soil that can be measured, the sizes of the other N sources and sinks must be estimated at the time of N fertilizer application (Cabrera et al. 1994). Such estimates, especially for N mineralization, are inaccurate and difficult to obtain with present technology. Rather than determining a value for each N source and sink, Magdoff et al. (1984) condensed all source and sink estimates into one single measurement. In the Magdoff pre-sidedress soil NO_3 test (PSNT) for corn (*Zea mays* L.), the N fertilizer recommendation is based on the amount of nitrate measured in the surface 30 cm of

soil when corn plants are 15 to 30 cm tall. This method, however, requires detailed soil sampling and sidedress application of fertilizer N, both time-consuming and expensive operations.

Other methods for estimating soil available N rely on the assumption that N losses through leaching and volatilization and N additions through rain and N fixation are relatively small during the growing season. With these methods, the N available to the crop would depend primarily on the initial available N, and the N mineralized from crop residues and soil organic matter during the growing season. Once an estimate of expected N mineralized and a measurement of initial available N is obtained, the amount of N fertilizer needed for the expected yield can be calculated. Of the many methods suggested to estimate the potentially available organic N in the soil, only two will be discussed and evaluated here. One is a biological method, originally proposed by Stanford and Smith (1972), that allows mineralization rates to be modeled. The other is a rapid chemical extraction method described by Gianello and Bremner (1986a).

The biological method requires data of N mineralized from long-term aerobic laboratory incubations fit with a kinetic equation (typically first order) from which the N mineralization potential (N_0) and the rate constant of mineralization (k) can be determined. The daily rate of N mineralization is then adjusted based on the actual soil temperature, using a Q_{10} of 2 within the temperature range of 5 to 35 °C (Stanford et al. 1973), and soil water contents. Stanford and Epstein (1974) reported highest N mineralization rates between soil water potentials of −10 kPa and −33 kPa for nine different soils and proposed a method to model the influence of water availability on N mineralization.

Although biological methods directly assess the N mineralized in soil, they require too much time for use in commercial soil testing laboratories. Chemical extraction methods therefore have more appeal. Many chemical methods have been proposed to extract a portion of the potentially mineralizable N, which would be highly correlated with and serve as an index of N that could potentially be mineralized from a given soil. The ammonium formed by the KCl-hydrolyzing method proposed by Oien and Selmer-Olsen (1980) and further developed and modified by Whitehead (1981) and Gianello and Bremner (1986a) is closely related to the N mineralized. Because of its relative simplicity, and its good relationship with N mineralized (Gianello and Bremner 1986b), we chose to use it in our research.

Research has shown that N mineralization from soil organic matter depends on the nature of the organo-mineral complex in the soil, especially particle size. Edwards and Bremner (1967) and Craswell et al. (1970) argue that the soil organic matter becomes inaccessible to microbes when soil aggregates are formed, a process that is facilitated by the presence of clay. Disruption of aggregates should therefore increase N mineralization. Waring and Bremner (1964) observed increases in N mineralization with decreasing soil mesh-size, possibly because soil particles were physically reduced in size and substrate became more available. Both Craswell and Waring (1972a, 1972b) and Rovira and Greacen (1957) also reported higher N mineralization after physical reduction of soil aggregate size. Rovira and Greacen (1957) and Hiura et al. (1976) suggested the clay/humus ratio as an index of potentially available organic N to microorganisms, and Cabrera and Kissel (1988c) proposed the clay/total N ratio to indicate the degree of protection that clays provide to organic matter against microbial decomposition. Based on this work, we propose to use clay and organic matter contents of soil within a field as an alternative method to describe the spatial variability of N mineralization rates.

The objective of this study was to accurately measure the amount of N mineralized at widely different locations in the field and then to determine if the amount mineralized might be estimated by three different approaches: (1) modeled from the soil organic matter and clay contents, (2) modeled from biological mineralization tests, or (3) estimated from a chemical extract. If the rate of N mineralization can be predicted using any of these methods, they may have value to estimate the spatial variability of N mineralization for use in N fertilizer application in precision farming.

Materials and methods

Because of the complexity of the methods used, we arranged them into sections according to the field measurement of N mineralization (Field N balance) and into sections that describe the various components of the methods used to predict N mineralization, i.e., the incubations required for the biological method, the

chemical and physical procedures, and the statistical methods used in modeling.

Field N balance

Cotton (*Gossypium hirsutum* L.) (Delta Pineland 90) was grown on a Coastal Plain field near Cordele, Georgia, 83.939030° to 83.947762° W; 32.004721° to 32.023520° N. Three study locations were selected within this field that varied widely in N mineralization potential. All other nutrients were non-limiting based on medium or above soil test levels for P and K and pH above 5.5 (Table 1). The selection of the study areas was based on 28 preliminary surface soil samples selected visually to include the range of soil organic C and clay contents in the field taken on December 9 and 10, 1997, and analyzed with the hot 2 *M* KCl method proposed by Gianello and Bremner (1986a) to estimate N mineralization potential. The three study areas were selected to cover the range in N mineralization potentials. The soils at these locations were classified as the Norfolk coarse-loamy (a taxadjunct to the Norfolk series), a coarse-loamy, kaolinitic, thermic Typic Kandiudults (designated North and Center), and as the Norfolk depressional, a fine-loamy, kaolinitic, thermic, Typic Kandiudults (designated South). The South site is located in a large depressional area of the field and as a result, it usually supports higher yields due to higher water availability than the crop from up-slope positions and due to its somewhat higher clay and silt contents and top soil depth. Cotton was the preceding crop in 1997.

At each study location a uniform area 18.3 × 22.0 m was chosen and divided into 24 plots in a randomized complete block design with four ranges of plots, each plot 4.60 m long and three rows wide (row spacing 96.5 cm). Four check plots 4.60 m long and six rows wide were established by selecting two adjacent plots within each range. The check plots did not receive any fertilizer and were used for the N balance study to estimate N mineralized from soil organic matter as well as to provide data of lint yield for a fertilizer rate study. Soil temperatures and soil water potentials at the 5 and 10 cm depths were recorded at the east and west side of the field, two locations that were representative for the soil in the three study locations. Temperature was measured hourly with a Cu-constantan thermocouple and a CR10X data recorder, from Campbell Scientific, Inc. (Logan, Utah). Soil water potential was measured with WATERMARK sensors from Irrometer Company, Inc. (Riverside, California) every 2 to 3 d and interpolated between measurements to estimate daily values.

The amount of N mineralized in the check plots of the field study was measured using procedures outlined by Schepers and Meisinger (1994). This technique is based on measurement of crop N uptake and a balance of inorganic N in the root zone from the beginning to the end of the N mineralization time period (Cabrera and Kissel 1988a). For our study, the approach involved measuring soil profile NO_3-N and NH_4-N to a depth of 120 cm at the beginning and end of the measurement period, measuring plant N uptake at the end of the measurement period, and correcting for 22.7 kg N ha^{-1} total applied by the farmer in four herbicide applications. The amount of N mineralized was calculated using Equation 1:

$$N_{min} = (NH_4\text{-}N + NO_3\text{-}N)_{end} - (NH_4\text{-}N + NO_3\text{-}N)_{start} + \text{plant } N_{uptake} + \text{weed } N_{uptake} - N_{fertilizer} \quad (1)$$

N losses were considered to be low and to not seriously affect the results. Leaching losses were estimated using the Leach N model (Wagenet and Hutson 1989) using soil physical properties and N mineralization from the North location, which was the sandiest and thus most susceptible to leaching losses.

Table 1. Soil type, and selected soil characteristics (0–15 cm depth) at the three field locations.

Location	Soil	Clay	Sand	Silt	Org. C	Org. N	C:N	pH[a]	P[b]	K[b]	N min. pot.
		(%)			(mg kg^{-1})				(kg ha^{-1})		(g NH_4-N kg^{-1})
North	Norfolk coarse-loamy	9.5	88.7	1.8	3971	301	13.2	6.1	108	63	2.1
Center	Norfolk coarse-loamy	10.4	85.6	4.0	3866	307	12.6	5.6	122	65	11.2
South	Norfolk depressional	13.5	76.5	10.0	5644	368	15.3	6.3	195	104	5.3

[a]Soil:water ratio = 1:1.
[b]Mehlich I extractable P and K as described in Reference Soil Test Methods for the Southern Region of the United States 1983.

Results of the simulation indicated leaching losses of 0.04 kg N ha^{-1} (in 0.05 cm drainage) by 120 d below 120 cm, the depth of sampling for the N balance. These results were consistent with the results of soil water sensors at a study area within 100 m of the North location that averaged −23 kPa at a depth of 92 cm on September 7. Sensors near the South location at 92 cm depth read 148 kPa on September 7, suggesting the absence of extensive drainage. These simulated drainage and leaching losses all occurred as a result of rains totaling 15.8 cm on September 2 and 3.

Beginning, 10 May 1998, and ending, September 7, 1998, soil samples were taken from an area, 0.965 m × 0.965 m, centered on one of the two center rows in each of the check plots to avoid any influence of adjacent plots. Samples were taken with an Oakfield 2 cm diameter soil probe at depths of 0–15, 15–30, 30–45, 45–60, 60–90, and 90–120 cm. Four samples were taken at equidistant spacing from each side of the row in a diagonal pattern, and all samples composited. The sampling diagonal was reversed for the September sample. Immediately after taking the deep soil samples in May, the sample holes were filled with a 50–50 mixture of clay (kaolinite) and sand to minimize uneven water flow patterns and to mark their location. The soil samples were stored in ice until return to the laboratory where they were stored at 5 °C and analyzed within one week. Within all check plots, the depth of topsoil and the bulk density of the topsoil were measured.

The plants from the 96.5 cm × 96.5 cm N balance study area were harvested 120 d after emergence (September 7, 1998) by pulling the plants and roots from the soil, separated into leaves and stems, seed cotton, and roots. Soil was shaken from the roots, and the roots were subsequently washed to remove any remaining soil. Any weeds within the sample area were also harvested.

Both roots and plant tops were oven-dried at 65 °C for 5 d and their dry weights recorded. They were then ground and stored until analysis. Seed cotton was air dried, its weight recorded, and ginned. The weights of cotton seeds, lint, and trash were recorded. The trash was not analyzed for N content because its weight was negligible. Kjeldahl analysis of cotton lint confirmed that its % N was near zero (< 0.05% N) and could be ignored.

Long term aerobic incubation

Soil samples from the 0–15, 15–30, and 30–45 cm depths were incubated in modified 60 ml Monoject® polypropylene syringes (Vigil and Kissel 1995) having a regular luer tip at 25 °C for 168 d to characterize N mineralization rates. Before laboratory incubation, acid-washed sand was mixed with the soil samples to support the structure of the soils higher in clay, to facilitate leaching.

The gravimetric water content (θ_g) of the soil samples was determined by oven drying a small subsample at 105 °C for 24 h. A sample of field-moist soil of weight equivalent to 30 g oven-dry soil was mixed with 30 g of acid-washed sand except for the sandier soils, which were the first two depths (0–15 cm and 15–30 cm) of the North I, North II, North III, and Center I plots and all depths (0–15 cm, 15–30 cm, and 30–45 cm) of the North IV plot. Each sample was then carefully packed into the prepared syringes by adding small portions of the soil and then tapping on the lab bench between additions to compact the soil as much as possible. After all soil was placed into the syringe, the volume occupied by the sample was measured by recording from the volume scale on the side of the syringe.

Water contents of the samples during incubation were kept near 50% of soil pore volume, calculated from bulk density and an assumed particle density of 2.65 Mg m^{-3}. Deionized water was added as needed to bring the water contents to 50% of pore volume. After allowing the water to infiltrate, 500 mg fiberglass 8-micron glass wool (with a tolerance of ± 50 mg) was placed on top of each sample to prevent dispersion during the leaching process. The final weight of each syringe, including the moisture adjusted soil and the glass wool, was recorded.

The syringes were held upright in Styrofoam® centrifuge tube trays with 3 mm holes through the base at each carving to allow air movement into both ends of the syringes during incubation. The trays were put in a humidity chamber (38-l glass aquarium) at 0.025 m above the bottom to minimize soil drying in the tubes. The aquarium was filled with water to a depth of 1 cm to provide a free water surface to maintain high humidity, and humidified air was pumped through at a rate of 1 l min^{-1} to maintain adequate oxygen levels.

The samples were leached after 0, 14, 28, 56, 84, 112, 140, and 168 d by placing the syringes onto a rubber stopper on top of a 500-ml Erlenmeyer sidearm flask by adding 66 ml of 0.01 *M* $CaCl_2$ in increments of 22 ml, followed by 25 ml of N-free nutrient solution containing 430.5 mg $CaSO_4$-$2H_2O$, 1.22 mg

KH_2PO_4, 8 mg K_2SO_4, and 120.4 mg Mg_2SO_4-$7H_2O$ per l. After drainage stopped, slight vacuum was applied to remove nutrient solution until the weight was equivalent to a water content of 50% water-filled pore space. The leachate was then made to 100 ml volume for analysis of NO_3-N and NH_4-N. Loss of moisture between the leaching intervals was less than 1 g for each syringe.

Chemical laboratory procedures

The N content of the seeds from the harvested and ginned cotton was determined by the Kjeldahl method (Baker and Thompson 1992). Eight replicates, three seeds each, were digested for each check plot to assure accuracy of the results. This method was employed because the cotton seeds could not be ground properly, due to their oil content. The digests were analyzed for NH_4-N with the salicylate-hypochlorite method (Crooke and Simpson 1971) using a Perstorp Analytical Autoanalyzer (500 series), Alpkem Corp., Clackamans, Oregon.

The C and N concentrations of the plant tops and roots were determined by analyzing a subsample of the dried and ground plant materials by the dry Micro-Dumas combustion with a NA 1500 C/H/N Analyzer, from Carlo Erba Strumentazione, Milan, Italy (Kirsten 1983).

Nitrogen mineralization capacity of soil was estimated by the hot 2 *M* KCl procedure of Gianello and Bremner (1986a). Briefly, this method involves heating 3 g of field moist soil in 20 ml 2 *M* KCl for 4 h at 100 °C. The KCl extract was then analyzed for NH_4-N as described above. The values were corrected by subtracting the NH_4-N concentration of unheated samples.

To determine the initial N concentration in the soil for the N balance, 3 g of field moist soil were extracted with 30 ml of 1 *M* KCl. After shaking for 30 s on a Vortex-Genie 2 stirrer to break up clods and to allow mixing of the soil with the solution, the samples were placed horizontally on an Eberbach automatic shaker at low speed for 1 h (125 cycles min^{-1}). After centrifugation, the supernatant was analyzed for NO_3-N with the Griess-Ilosvay technique (Keeney and Nelson 1982) using an Alpkem Autoanalyzer (300 series), Alpkem Corp., and for NH_4-N as described above.

For total C and N analysis of soils, the samples were air dried and passed through a 2 mm sieve to break up big clods and remove small rocks and crop residues (<1% of sample weight). About 30 g of each sample were then ball milled for 5 min and a subsample analyzed by the dry Micro-Dumas combustion with a NA 1500 C/H/N Analyzer, from Carlo Erba Strumentazione (Kirsten 1983).

Physical laboratory procedures

For particle size analysis, the samples were air dried and sieved as described in the C and N analysis above. The particle size distribution of the samples was then determined by the pipette method as described by Kilmer and Alexander (1949).

Moisture retention curves were determined on two soil samples, one sandy (100 g kg^{-1} clay, 860 g kg^{-1} sand), the other with more clay (190 g kg^{-1} clay, 750 g kg^{-1} sand) to represent the water holding properties of the soils. These soils were air dried and sieved as described above. Three Tempe Pressure Cells (Cat. # 1450, Soil Moisture Equipment Corp., Santa Barbara, CA) were packed with each sample. Ceramic plates saturated with 0.01 *M* $CaCl_2$ solution were placed at the bottom of the cores. Then the air dried and sieved soils were packed into the cells. To prevent clay dispersion, the cells were allowed to wet up with 0.01 *M* $CaCl_2$ solution by capillarity-rise until free solution appeared on the surface.

Over a period of several weeks, pressures of 0.7, 1.5, 3.0, 5.9, 13.3, 26.0, 46.7, and 93.3 kPa were applied. The mass of the cells was recorded daily until a weight difference in a 24 h period was less than 0.3 g. Then the pressure was changed to the next highest value. After the last measurement at −93.3 kPa, the Tempe Pressure Cell was disassembled and the soil oven-dried at 105 °C for 24 h and its mass recorded. In a pressure chamber, θ_g for 1.5 MPa was obtained by setting samples of soil on a ceramic plate and saturating them with 0.01 *M* $CaCl_2$, followed by application of 1.5 MPa pressure. After equilibrium, water contents were determined by oven-drying at 105 °C.

For all pressure settings of each sample, θ_g was converted into volumetric water contents θ_v using the bulk density of the packed cores. To obtain a moisture release curve for the two soils, the following function [2] (Van Genuchten 1980) was fitted to the data of each sample:

$$\theta\,\mathrm{v(h)} = \left([1 + (-\alpha \cdot h)^n]^{(\frac{1}{n} - 1)} \right) \cdot (\theta_s - \theta_r) + \theta_r \quad (2)$$

where h is the negative water pressure in cm of H_2O,

θ_s the volumetric water content at saturation, and θ_r the residual water content; α and n are fitting parameters. The equation was first fitted for each of the six samples individually, setting θ_s equal to φ (total pore space) based on ρ_b, and using the Levenberg–Marquardt algorithm (Minerr function of Mathcad) described in Mathcad 7 Professional from MathSoft, Inc. Then the three values for θ_r, α, and n for each of the two soils were averaged. To predict field water content, θ_s was adjusted to φ based on the measured field bulk density of 1.53 Mg m^{-3} for both soils.

Statistical analysis

We used PROC NLIN in SAS (SAS Institute Inc. 1985) to fit the data of cumulative net N mineralized with time (N_t) in the laboratory incubation to Equations 3 and 4, where t is time, N_0 is the N mineralization potential, k is a first-order rate coefficient of N mineralization, and k_0 is a zero-order rate coefficient of N mineralization.

$$N_t = N_0 \cdot (1 - e^{-kt}) \quad (3)$$

$$N_t = k_0 \cdot t \quad (4)$$

Because Equation 4 yielded lower root mean square errors than Equation 3, we selected the linear model to describe our data. Also, to obtain better estimates of k_0, we fitted Equation 4 to incremental instead of cumulative data of net N mineralized (Hess and Schmidt 1994; Ellert and Bettany 1988).

Prediction of N mineralized in the field

To adjust mineralization for non-optimum conditions of soil water and temperature in the field, we used an N mineralization factor WTF (Equation 5) that accounts for the influence of soil water content (WF_t) and soil temperature (TF_t) on the rate of N mineralization. Based on the moisture release curve, the soil water potential measurements from the field were converted into volumetric water contents. Water content for maximum N mineralization was at a soil water potential of -10 kPa (Stanford and Epstein 1974). The water factor ($0 < WF_t \leq 1$) was then calculated for each day as the ratio of measured over optimum volumetric soil water content. The temperature factor ($0 < TF_t$) was calculated based on a Q_{10} of 2 and an average daily soil temperature computed from the hourly field measurements ($TF_t = 1$ at 25 °C, the temperature of the laboratory incubations). When average soil temperature exceeded 25 °C, the daily value of the temperature factor exceeded 1. To obtain the N mineralization factor for each depth (5 cm and 10 cm) and each location, the water and temperature factors for each day were multiplied and their products added (Equation 5). The calculated values for the two depths were then averaged for each location.

$$WTF = \sum_{t=0}^{120} WF_t TF_t \quad (5)$$

The N mineralization factor was 85.4 for the North and Center and 132.6 for the South. Values of WTF may exceed 120 if the average daily soil temperatures exceed 25 °C (and WF exceeds 1) for the period of the simulation. For each location, the respective k_0 was multiplied by the N mineralization factor calculated from either the east (North and Center) or the west (South) side of the field (Equation 6), and by the bulk density (BD) of the soil layer under consideration.

$$N_{min} = k_0 \cdot WTF \times BD \times 1.5 \quad (6)$$

The factor of 1.5 was derived by taking into account the thickness of each soil layer (15 cm) as well as the conversion factors required to express N_{min} in kg N ha^{-1}. To predict the amount of N mineralized from the upper 30 cm, this calculation was conducted independently for each layer (0–15 and 15–30 cm) and the results were added.

Results and discussion

Field N balance

Profile inorganic N at the May and September sampling dates, crop N uptake at the September sampling, and the values of N mineralization calculated from these values using Equation 1, are all shown in Table 2. The values of soil profile inorganic N include ammonium and nitrate N to a depth of 120 cm. In general, the values of profile inorganic N were low at the May sampling and they were only marginally higher at the September sampling at the Center and South locations. In most cases, the values of plant uptake were either similar or larger than the values of N mineralized. As expected from the hot 2 *M* KCl measurements of surface soil from the preliminary study, N mineralized differed at the three locations. The average N mineralized at the North location was 26 kg N ha^{-1}, with 53 kg N ha^{-1} at the Center

Table 2. Inorganic N in the 0–120 cm soil depth at two sampling dates, plant N uptake, and N mineralized calculated using Equation 1.

Location	Plot	May profile inorganic N (kg N ha^{-1})	Sept. profile inorganic N (kg N ha^{-1})	Plant N uptake (kg N ha^{-1})	N mineralized[a,b] (kg N ha^{-1})
North	1	26	16	59	27
	2	31	20	47	13
	3	26	19	50	21
	4	25	15	75	42
	Mean	27	18	58	26
Center	1	27	51	62	64
	2	23	27	75	56
	3	23	38	48	40
	4	35	33	74	50
	Mean	27	37	65	53
South	1	37	43	92	75
	2	36	62	74	78
	3	51	42	85	53
	4	34	39	79	62
	Mean	40	47	83	67

[a] During the growing season, an additional 22.7 kg N ha^{-1} in the form of urea was foliar applied together with a herbicide at a rate of 7.7 kg N ha^{-1} (day 69) and 5.0 kg N ha^{-1} each on days 80, 88, and 99.
[b] LSD = 14, $\alpha = 0.10$.

location and 67 kg N ha^{-1} at the South location during the 120 d measurement period. Those differences were statistically significant (LSD = 14 kg N ha^{-1}, $\alpha = 0.1$). The individual values of N mineralized for each plot in the field ranged from 13 to 78 kg N ha^{-1}.

Predicting N mineralized from surface soil properties

We regressed the values of N mineralized in the field on the total C, total N, the C:N ratio, and clay content of the corresponding 0–15 cm soil samples. Only the clay content in the soil (Table 3, Equation 7) was statistically significant in explaining N mineralization ($\alpha = 0.05$). When the measured contents for total C, total N, and clay were multiplied by their respective bulk densities the predictive power of the individual variables increased slightly, but with the exception of clay content (Table 3, Equation 8), they were still statistically not significant.

Interaction terms were included in the model, but no statistically significant relationships between the tested interaction terms and N mineralization were found except for those that included clay content. The interaction terms that included clay resulted in statistically significant models, but those did not achieve a better prediction of the measured N mineralized than the model that was the product of clay content and bulk density of the 0–15 cm layer (Table 3, Equation 8).

The regression analysis was repeated for the other two depths (15–30 cm and 30–45 cm) and all depths together. Again, linear and exponential interaction terms were systematically formed and included. None of the independent variables besides clay and its interaction terms explained the field N mineralized with statistical significance. The analysis described in this and the previous two paragraphs was repeated for

Table 3. Equations for predicting N mineralization potential (y, kg N ha^{-1}) and k_0 (y, mg N kg^{-1} d^{-1}) based on clay concentration (x_1, %) and bulk density (x_2, Mg m^{-3}) of the 0–15 cm soil depth, n = 12.

Equation	Relationship	Equation	Adj. r^2	*p*-value
7	$N_{minField}$ vs. clay	$y = -10.365 + 5.287 \cdot x_1$	0.33	0.0288
8	$N_{minField}$ vs. clay × bulk density	$y = -9.905 + 3.386 \cdot x_1 \cdot x_2$	0.40	0.0159
9	k_0 vs. clay	$y = -0.063 + 0.013 \cdot x_1$	0.66	0.0009
10	k_0 vs. clay × bulk density	$y = -0.050 + 0.007 \cdot x_1 \cdot x_2$	0.63	0.0012

the rate of mineralization in the laboratory incubations (k_0). The results were similar, i.e. only models which included clay or its interaction terms were statistically significant (Table 3, Equations 9 and 10).

The positive correlation between N mineralized and clay content may have been caused by differences in the amount of available water and soil water storage capacity of the soils. This may be due to one of the following factors: (1) water contents might be nearer to their optimum for N mineralization on soils with higher clay contents, and (2) more crop biomass may have been produced each year on the areas of higher clay contents, leading to higher soil microbial biomass and more N mineralization.

To address the first point, soils with the highest clay contents in the South generally had higher water contents throughout the mineralization measurement period (data not shown). For the period from June 24, 1998 until September 1, 1998, whenever soil water potentials were less than or equal to −30 kPa, the sandier North location was drier than the South location for all except two days. Better water availability at the South location was also reflected in the higher value of WTF of Equation 5 calculated for the 120 d period of mineralization measurement in the field. These values were 85.4 for the North and Center and 132.6 for the South. Higher WTF in the South was primarily the result of differences in soil water, because when we used the soil temperature values of North and Center in calculating the WTF for the South, WTF changed very little (130.3 vs. 132.6).

Soil clay contents may also have indirectly influenced the N mineralization through its influence on biomass production. The differences in N mineralization may be due in part to higher crop production from better water availability in those areas with higher clay contents. We found that the previous years plant biomass (the 1997 crop) in the selected study areas (based on a calculation of the vegetation index from an infrared image of the field taken on September 8, 1997) was highest in the South (8784 kg ha^{-1}), followed by the Center (2108 kg ha^{-1}) and the North (1700 kg ha^{-1}). Water movement (both surface and subsurface) from upslope areas is especially likely in the South location, due to its relatively low topographic position. N mineralization depends in part on the quality and quantity of crop residues that are returned to the soil. Larger quantities of crop residues would contain more N that will then result in more N mineralized over time.

Long-term aerobic incubation

The cumulative N mineralized in the long-term aerobic laboratory incubations was first regressed on time using Equation 3 (Stanford and Smith 1972). In contrast to other research results (Deans et al. 1986; Cabrera and Kissel 1988b), our data fit was better using a linear Equation 4. Similar results for Georgia soils were obtained by Cabrera (1993). Cumulative N mineralized from the four replicates of the North location at the 0–15 cm depth is shown in Figure 1 as an example, illustrating an over twofold variation. The values of k_0 and the root mean square error (RMSE) from the regression analysis are shown in Table 4 for all data. The values of k_0 were greatest at the 0–15 cm soil depths, intermediate at the 15–30 cm depths, and lowest at the 30–45 cm depths. Values of RMSE are generally small, indicating that the models fit the data well.

Predicting N mineralized in the field from biological and chemical methods

Using the k_0 values generated from the regression analysis, and then applying Equations 5 and 6, N mineralized in the field was predicted for the 12 individual plots. The relationship between the predicted and the measured field values for the surface 0–15 cm soil is shown in Figure 2. The regression of predicted and measured N mineralized was statistical-

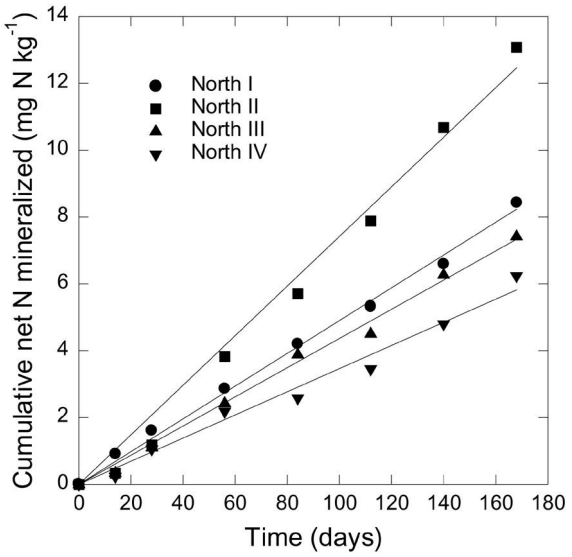

Figure 1. Cumulative N mineralized during the incubation from the four replicates of the North location at the 0–15 cm depth.

Table 4. Values of k_0 (Equation 4) and the root mean square error from the regression analysis (RMSE) from the aerobic laboratory incubation determined with Equation 4.

		Location					
		North		Center		South	
Rep.	Depth (m)	k_0 (mg N kg^{-1} d^{-1})	RMSE (mg N kg^{-1})	k_0 (mg N kg^{-1} d^{-1})	RMSE (mg N kg^{-1})	k_0 (mg N kg^{-1} d^{-1})	RMSE (mg N kg^{-1})
I	0–0.15	0.0495	0.235	0.0866	0.609	0.1405	1.0719
	0.15–0.30	0.0277	0.173	0.0563	0.345	0.0114	0.151
	0.30–0.45	0.0020	0.045	0.0163	1.388	0.0036	0.036
II	0–0.15	0.0811	0.471	0.0531	0.390	0.1193	0.583
	0.15–0.30	0.0186	0.250	0.0136	0.260	0.0299	0.366
	0.30–0.45	0.0086	0.267	0.0031	0.071	0.0059	0.137
III	0–0.15	0.0446	0.371	0.0499	0.612	0.1394	0.963
	0.15–0.30	0.0323	0.263	0.0298	0.424	0.0424	0.533
	0.30–0.45	0.0056	0.122	0.0053	0.128	0.0052	0.070
IV	0–0.15	0.0371	0.382	0.0497	0.188	0.0937	0.525
	0.15–0.30	0.0239	0.258	0.0314	0.555	0.0149	0.104
	0.30–0.45	0.0028	0.082	0.0036	0.071	0.0056	0.083

ly significant ($\alpha = 0.05$), with coefficient of determination $r^2 = 0.43$, but with considerable error at low values of predicted mineralization. However, compared to the 1:1 line in Figure 2, the model greatly underpredicted the N mineralized in 11 of the 12 plots. For example, at values of measured N mineralized of 50 kg N ha^{-1}, the model would predict only 45% of that value.

Although soil temperature and soil water contents were not available for the 15–30 cm depth, we estimated from nearby data of soil water potential taken throughout the growing season at 0.2 m that the water potentials were similar to those of the 0–15 cm depth. We therefore applied the calculated values of WTF for the 0–15 cm layer to the k_0 values of the 15–30 cm depth for all 12 plots. The value of N mineralized predicted using this procedure was added to the value predicted from the 0–15 cm depth for all plots. The measured N mineralized was then regressed on this sum, resulting in $r^2 = 0.41$. There was some improvement in that the regression line was closer to the 1:1 line; however, the model that included 0–30 cm soil depths still greatly underpredicted the amount of N mineralized, i.e. at values of measured N mineralized of 50 kg N ha^{-1}, the model only predicted 58% of that value. As the values of k_0 were quite low for the 30–45 cm depth, this layer would not have contributed significantly to the prediction.

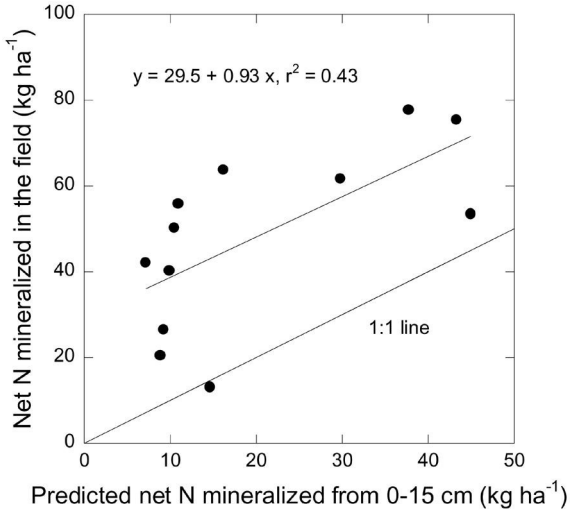

Figure 2. N mineralized in the field and predicted values of N mineralized from the 0–15 cm depth determined with Equation 6.

The underprediction of the model may be due to the fact that in the laboratory, the soils were not exposed to repeated wetting and drying as they are regularly in the field. Previous research by Campbell et al. (1988) and Herlihy (1979) has also shown an underprediction of mineralization of soils that are exposed to repeated wetting and drying. Under controlled laboratory conditions, Cabrera (1993) found that one drying and wetting cycle increased the zero-order mineralization rate coefficient (k_0) by an average of 22% for the five soils in the study. In addition to increasing the zero-order rate coefficient, drying and wetting generated a mineralizable pool of N that decomposed according to first-order kinetics. On average, the size of this mineralizable pool corresponded to 0.6% of the total soil N and was completely decomposed within

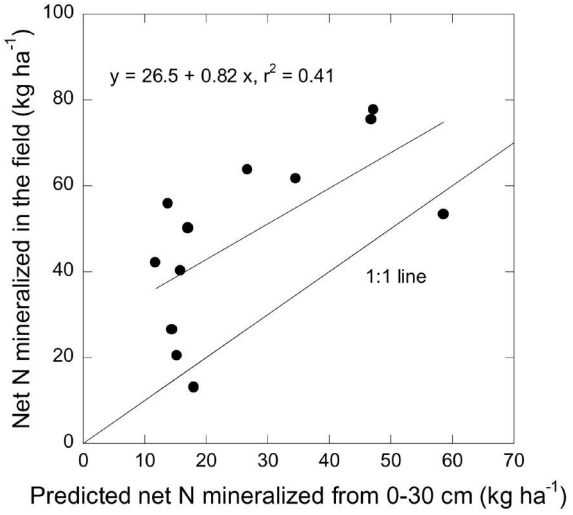

Figure 3. N mineralized in the field and predicted values of N mineralized from the 0–30 cm depth determined with Equation 6.

the first 4 days after rewetting. Repeated wetting and drying, as occurs in the field, is likely to have an even larger effect on N mineralization.

The N mineralization potential of the surface 0–15 cm soil was also determined with the hot 2 *M* KCl method (Gianello and Bremner 1986a). The relationship between N mineralized in the field and the NH_4-N released by hot 2 *M* KCl was statistically significant ($\alpha = 0.05$), and had a coefficient of determination, $r^2 = 0.60$ (Figure 4). Based on this result, it appears that

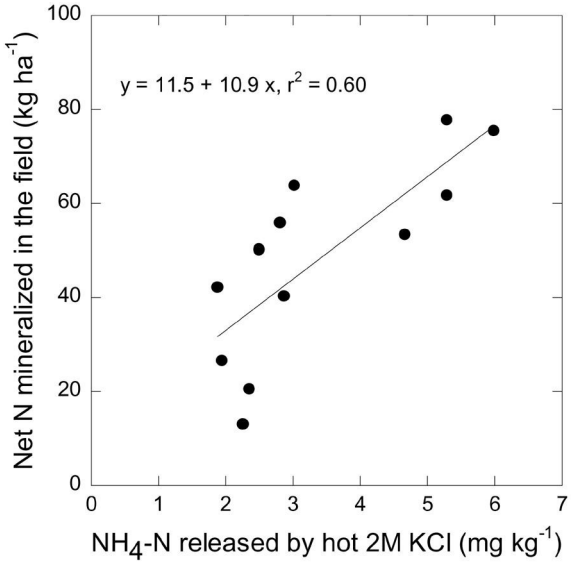

Figure 4. N mineralized in the field and NH_4-N concentration in the supernatant after extraction with hot 2 *M* KCl (0–15 cm).

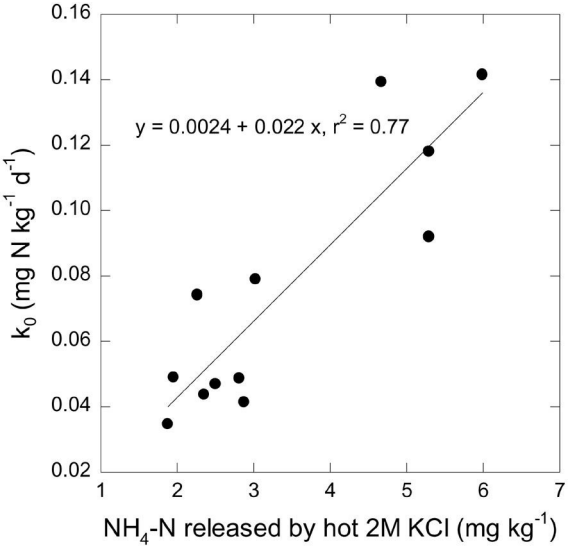

Figure 5. N released per day during the aerobic laboratory incubation (k_0) and NH_4-N concentration in the supernatant after extraction with hot 2 *M* KCl (0–15 cm).

the method of Gianello and Bremner (1986a) has some potential to estimate the amount of N that will be mineralized in the field. This is in agreement with findings of Oien and Selmer-Olsen (1980), Whitehead (1981) and Gianello and Bremner (1986a, 1986b).

The zero-order rate constant of mineralization (k_0) was significantly related to the NH_4-N released by the hot 2 *M* KCl method ($\alpha = 0.05$ and $r^2 = 0.77$), as shown in Figure 5. The better fit for the laboratory k_0's compared to field N mineralized on hot 2 *M* KCl could be due to the fact that the measurements were more controlled in the lab and/or that wetting and drying in the field reduced the goodness of fit.

Conclusions

Nitrogen mineralized in the field, as determined by the N balance approach, varied widely across the three study locations. Three methods to predict the N mineralized in the field were evaluated, one based on surface soil properties, another based on a biological method and the third based on a chemical method. Organic matter concentrations of surface soil could not be used to predict N mineralized in the field. The surface soil clay contents were positively correlated with the N mineralized in the field, but this soil property is not likely to be useful for future estimates of the N mineralization potential over a wide geo-

graphical area, since other studies have found that clay sometimes has the effect of reducing N mineralization. Both the hot 2 *M* KCl method as a chemical index and the laboratory incubation as a biological index were significantly correlated with the N mineralized and are therefore potentially useful indices for the N mineralized in the field. Based on the laboratory incubation results, most of the N mineralized in the field comes from the 0–15 cm and 15–30 cm depths. The 0–15 cm layer contributed an average of 69% of the N mineralized from the top 0–45 cm, the 15–30 cm soil depth 27%, and the 30–45 cm depth 4%. Since the 0–15 cm layer supplies the majority of the N mineralized, a chemical test of this layer may have promise for estimating the N mineralized.

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