Assessing Indices for Predicting Potential Nitrogen Mineralization in Soils under Different Management Systems

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A reliable laboratory index of N availability would be useful for making N recommendations, but no single approach has received broad acceptance across a wide range of soils. We compared several indices over a range of soil conditions to test the possibility of combining indices for predicting potentially mineralizable N (N_0). Soils (0–5 and 5–15 cm) from nine tillage studies across the southern USA were used in the evaluations. Long-term incubation data were fit to a first-order exponential equation to determine N_0, k (mineralization rate), and N_0^* (N_0 estimated with a fixed k equal to 0.054 wk^{-1}). Out of 13 indices, five [total C (TC), total N (TN), N mineralized by hot KCl (Hot_N), anaerobic N (Ana_N), and N mineralized in 24 d (Nmin_24)] were strongly correlated to N_0 ($r > 0.85$) and had linear regressions with $r^2 > 0.60$. None of the indices were good predictors of k. Correlations between indices and N_0^* improved compared with N_0, ranging from $r = 0.90$ to 0.95. Total N and flush of CO_2 determined after 3 d (Fl_CO2) produced the best multiple regression for predicting N_0 ($R^2 = 0.85$) while the best combination for predicting N_0^* ($R^2 = 0.94$) included TN, Fl_CO2, Cold_N, and NaOH_N. Combining indices appears promising for predicting potentially mineralizable N, and because TN and Fl_CO2 are rapid and simple, this approach could be easily adopted by soil testing laboratories.

Abbreviations: Ana_N, anaerobic N mineralization; TC, total carbon; Ca_hypcl, calcium hypochlorite; Cold_N, KCl extractable NO_3–N; CT, conventional tillage; Fl_CO2, flush of CO_2 during 3 d; Hot_N, hot KCl extractable NH_4–N; Hyd_N, hydrolyzable N; k, mineralization rate constant; TN, total nitrogen; NaOH_N, sodium hydroxide distillable N; N_0, potentially mineralizable N; N_0^*, value of N_0 determined using a fixed value for k; Nmin_24, N mineralization during 24 d; NP, not plowed (prairie soil); NT, no-Tillage; NT+SS, no-tillage with non-inversion subsurface deep tillage; PB_N, phosphate-borate distillable N; POMC, particulate organic matter C; POMN, particulate organic matter N; SM, stubble mulch tillage (sweeps to undercut weeds); ST, strip tillage (in-row subsoil for disruption of subsurface pan and coulters for preparation of narrow strip of tilled soil).

Availability of N from soil organic matter during a growing season is a function of many biotic and abiotic factors, including cropping history, management, climate (temperature and water availability), and the interacting effects of soil C cycling (Griffin, 2008). Estimating the N mineralization potential of a soil is of considerable importance for maximizing N-use efficiency from all N sources and minimizing environmental losses. Efforts to develop quick biological or chemical methods for identifying the mineralization potential of organic N have a long history (reviewed by Bremner, 1965; Keeney, 1982; Bundy and Meisinger, 1994; Griffin, 2008) with various levels of success. Several of these methods closely correspond to the mineralizable N component (Griffin, 2008).

Stanford and Smith (1972) established the concept of potentially mineralizable N (N_0) as a quantifiable soil N pool. They used the biologically based, long-term aerobic incubation method to measure net N mineralization over 210 d to estimate N_0 along with the N mineralization rate constant (k) using a first-order exponential function:

$$N_t = N_0(1 - e^{-kt}) \qquad [1]$$

where N_t is the cumulative N mineralized at Week t, N_0 is the maximum mineralizable N, k is the mineralization rate constant (expressed on a wk^{-1} basis), and time (t) in weeks. This is the standard method against which most others are assessed, and it has been widely used for evaluating environmental, soil, and management impacts on N mineralization.

A second widely adopted approach used to identify the pool of potentially mineralizable N and compare more rapid laboratory methods is short-term anaerobic incubation (Waring and Bremner, 1964). This procedure quantifies the NH_4–N released from microbes killed by the anoxic conditions in a soil-water slurry incubated for 7 or 14 d under anaerobic conditions. Gianello and Bremner (1986b) observed a correlation (r) of 0.96 between a 7-d anaerobic incubation and net N mineralized during an 84-d aerobic incubation for a range of soils from Iowa, USA. Results from Chan (1997) for pasture and cropland soils show a strong relationship between these two methods ($r = 0.94$), and also shows that N_0 was approximately 2.25 times the amount of N released during the anaerobic incubation.

Total soil N (and C) concentration has been used as an index of N availability for plant growth with mixed results. In some cases, the relationship is significant, but not strong enough to be predictive. Hassink (1994) and Selles et al. (1999) observed weak correlations between TN concentration and N mineralization for soils assessed from a broad geographical area, while Marion et al. (1981), Hadas et al. (1986a; 1986b), Gianello and Bremner (1986b), and Springob and Kirchmann (2003) observed much stronger relationships when soils originated from a small geographical area.

A variety of chemical extraction and distillation methods for N availability have been developed, including extraction in weak salt solutions (Keeney and Bremner, 1966), stronger salt solutions (Gianello and Bremner, 1986a; 1986b) and alkali hydrolysis in NaOH (Stanford, 1978). Of these methods, extraction with hot or cold KCl (Hot_N or Cold_N) and distillation of NH_4–N with either a pH 11.2 phosphate-borate buffer solution (PB_N) or a NaOH solution (NaOH_N) have shown promise. Øien and Selmer-Olsen (1980) and Whitehead (1981) proposed using hot KCl–extractable NH_4–N as an index of available N on the basis of a close correlation with plant N uptake. Gianello and Bremner (1986a) found N mineralization and hot KCl–extractable NH_4–N corrected for initial mineral N (hydrolyzable N, Hyd_N) were highly correlated ($r = 0.95$). Other reports have found smaller correlations (Groot and Houba, 1995; Selles et al., 1999; Curtin and Wen, 1999; Jalil et al., 1996). Curtin and Wen (1999) and Jalil et al. (1996) found the correlation between hot KCl–extractable NH_4–N and N_0 was much stronger when values were not corrected for the initial NH_4–N concentration extracted in cold KCl.

Gianello and Bremner (1986b, 1988) observed a strong correlation between mineralizable N and PB_N. They proposed that PB_N measures a combination of NH_4–N and some amino acids. Jalil et al. (1996) found the correlation between N_0 and PB_N was similar to the correlation with Hot_N ($r = 0.78$ and 0.73, respectively) for 42 soils representing all agroecological regions in Saskatchewan, Canada. When narrowed to a comparison of long-term cropping treatments within one soil type, the correlations increased to 0.92 and 0.88, respectively. Vanotti et al. (1995) showed that correlations with PB_N were good for field indicators of N availability, and laboratory-measured labile fractions of soil organic matter, with most having $r > 0.70$.

Sharifi et al. (2007) recently proposed assessing potentially available N with a modification of the NaOH distillation method (NaOH_N) evaluated by Stanford (1978). Sharifi et al. (2007) found that NaOH_N was significantly correlated with both N mineralized after a 24-wk aerobic incubation ($r = 0.61$) and the Illinois soil N test ($r = 0.92$; ISNT; Khan et al., 2001). Bushong et al. (2007) found NaOH_N and ISNT were highly correlated ($r = 0.90$) for 25 soils from agricultural sites across the South-Central and Midwest USA. Both indices had similar correlations with potential N mineralization ($r = 0.60$) measured by anaerobic incubation.

Although no single N availability index has proven robust enough for broad acceptance, continued work is essential to accumulate critical experimental evidence across a wide range of soils to help identify appropriate procedures (Balkcom et al., 2003). Gallagher and Bartholomew (1964) found that predictions of N availability were improved when N test methods and soil properties were combined in multiple regressions. Wang and Li (1991) also found that combining indices improved predictions of plant N uptake. Chalk and Waring (1970) on the other hand reported little improvement in relationships from combining individual measurements in multiple regressions for predicting N availability.

Economic and environmental concerns continue to reinforce the need for routine methods of estimating N availability similar to methods for phosphorus, potassium, and other nutrients. Soil testing laboratories could use a reliable index as a basis for more accurate recommendations of fertilizer N. Our objective was to evaluate the potential for developing a rapid N assessment tool using N indices, either individually or in combinations, to predict potential N availability over a range of pedogenically distinct soils from the southern region of the USA.

MATERIALS AND METHODS
Soils

Several methods for assessing potential N availability (Table 1) were evaluated using soil samples collected from nine sites in the southern USA (Table 2). Tillage treatments and the crop before sampling are presented in Table 2. Sites were chosen to represent a range of parent materials under different management systems. Eight of the sites included comparisons between conservation tillage and more intensive tillage practices, while one location provided comparison between a non-disturbed prairie and a conservation tillage system. All soils were sampled in late winter before planting the 2005 summer crop by compositing four to eight samples collected from the 0- to 5- and the 5- to 15-cm depths. At each location, approximately 5 kg of soil was collected and dried at 40°C to achieve constant moisture conditions before shipping to Watkinsville, GA. Soils were slightly crushed to pass through a 4.75-mm sieve, and dried at 40°C an additional 3 d. Soils were stored at

Table 1. Laboratory methods used for determining potential N mineralization.

Measurement	Abbreviation	Type	Units	Reference
Total Carbon	TC	Chemical	g kg^{-1}	Bremner, 1996
Total Nitrogen	TN	Chemical	mg kg^{-1}	Nelson and Sommers, 1996
Particulate organic matter C	POMC	Chemical	mg kg^{-1}	Franzluebbers et al., 2000
Particulate organic matter N	POMN	Chemical	mg kg^{-1}	Franzluebbers et al., 2000
KCl extractable NO_3–N	Cold_N	Extraction	mg kg^{-1}	Mulvaney, 1996
Hot KCl extractable NH_4–N	Hot_N	Extraction	mg kg^{-1}	Gianello and Bremner, 1986a
Hydrolyzable N	Hyd_N	Extraction	mg kg^{-1}	Gianello and Bremner, 1986a
Sodium Hydroxide distillable N	NaOH_N	Distillation	mg kg^{-1}	Sharifi et al., 2007
Phosphate-borate distillable N	PB_N	Distillation	mg kg^{-1}	Gianello and Bremner, 1986a, 1988
Anaerobic N mineralization	Ana_N	Incubation	mg kg^{-1}	Waring and Bremner, 1964
N mineralization during 24 d	Nmin_24	Incubation	mg kg^{-1}	Franzluebbers et al., 2000
Flush of CO_2 during 3 d	Fl_CO2	Incubation	mg kg^{-1}	Franzluebbers et al., 2000
Calcium hypochlorite	Ca_hypcl	Chemical	kPa	Picone et al., 2002

room temperature after drying. For the laboratory methods, soils were passed through a 2-mm sieve, and three replicate samples were assayed with each method except for the distillation procedures in which two replicates were used.

Routine soil analyses (pH and plant nutrients) were conducted at the University of Georgia Soil, Plant, and Water Analysis Laboratory (Athens, GA). Total C and N were determined by dry combustion using a TruSpec CN analyzer (LECO Corporation, St. Joseph, MI). For the Temple soils, inorganic C was determined gravimetrically from loss of CO_2 following treatment with acid (J.B. Rodriguez, 2008, personal communication). Sand, silt, and clay were determined by the procedure of Kettler et al. (2001). The sand fraction (>0.05-mm diam.) was ball milled, and C and N were determined by dry combustion to estimate particulate organic matter C and N (POMC and POMN, respectively) per gram of air-dry soil (Franzluebbers et al., 2000).

Nitrogen Mineralization Indices
Long-Term Incubation

A modification of the non-leached approach of Wang et al. (2003) was used in the long-term (41 wk) incubation for determining N_0 and k. Soils were weighed (10 g) in triplicate into 50 mL centrifuge tubes, and water was added to reach 50% water filled pore space. Samples were incubated in a large chamber at 35°C. They were kept inside closed plastic boxes containing six vials of water to help maintain humidity. Boxes were open two to three times each week for ventilation, and their positions inside the chamber were re-randomized. Water content was adjusted every 3 wk by weighing and adding water to replace losses due to evaporation. Mineral N was extracted at Weeks 0, 2, 4, 6, 9, 12, 16, 20, 24, 29, 35, and 41 by adding 40 mL of 2 mol L^{-1} KCl, shaking for 1 h, and filtering through Whatman No. 42 filter paper. Extracts were frozen until analyzed for NO_3–N and NH_4–N on an automated analyzer (Keeney and Nelson, 1982). Cumulative N mineralized was calculated by summing the measured NO_3–N and NH_4–N for each sampling date. Initial mineral N content at Time 0 was not subtracted from values measured on subsequent dates. We used this approach because the flush of N released on rewetting of the soil would most likely be readily immobilized and mineralized at an unknown rate over the course of the incubation. The data from weeks 2 to 41 were used to calculate N_0 and k in Eq. 1 with the MODEL procedure of the Statistical Analysis System (SAS) version 9.2 (SAS Institute Inc., 2008). Parameters were fit by site, tillage treatment, and depth using nonlinear regression. The use of a fixed value of k (0.054 wk^{-1}) in the single exponential model for determining N_0 (N_0^*), as proposed by Wang et al. (2003), was ex-

plored and determined with the same model fitting procedures. Wang et al. (2003) used the average value of k determined by Stanford and Smith (1972) for 39 soils, to eliminate the effects of the colinearity of parameters when simultaneously fitting N_0 and k, and to allow N_0 to be a distinct indicator of the size of the potentially mineralizable N pool directly comparable among soils.

Extractable Inorganic Nitrogen (Cold_N)

The Week 0 soils of the long-term incubation were used for determining the initial amount of NO_3–N in soils. Ten grams of soil were extracted with 40 mL of 2 mol L^{-1} KCl, and designated as Cold_N. The NH_4–N (Cold_NH_4) determined in the same extract was used as the initial value for calculation of some of the indices below.

Hydrolyzable (Hyd_N) and Hot (Hot_N) KCl Extractable NH_4

Hot extractable N (Gianello and Bremner, 1986b) was determined by weighing 3 g of soil into a 50-mL centrifuge tube, adding 20 mL of 2 mol L^{-1} KCl, and incubating the samples at 100°C for 4 h in a water bath. After cooling to room temperature, the samples were filtered, and the extracts were frozen for NH_4–N analysis as described above. Hydrolyzable N (Hyd_N) was calculated by subtracting Cold_NH_4 (above) from NH_4–N released by heating (Gianello and Bremner, 1986b). Jalil et al. (1996) and Curtin and Wen (1999) reported a better correlation with mineralizable N when the initial NH_4–N is not subtracted, which we designated as Hot_N.

Sodium Hydroxide Distillable Nitrogen

Soils were analyzed for NaOH_N following the Sharifi et al. (2008) modification of the method developed by Stanford (1978). A 5-g soil sample was added to a distillation flask with 40 mL of 12.5 mol L^{-1} NaOH, and distilled until 40 mL was collected in 5 mL of 4% (w/v) boric acid solution. The volume extracted was used as the determining factor for ending the distillation rather than time due to slight differences in the rate of steam delivery between the two distillation units. The NH_4–N content of the distillate was determined from titration with a standard solution of 0.005 mol L^{-1} HCl in the presence of a mixed indicator (bromocresol green and methyl red).

Phosphate-Borate Distillable Nitrogen

The PB_N was determined as described by Gianello and Bremner (1988). A 4-g soil sample was direct steam distilled with 40 mL of phosphate–

Table 2. Soil locations, type, and cropping system history of experiments used in evaluation of N mineralization indices.

ID	Location	State	Soil type	Soil series	Year started	Tillage†	Cover crop	Previous crop	Rotation	Study Name
1	Shorter	AL	fine-loamy, siliceous, subactive, thermic Typic Paleudult	Bama	2001	CT/ NT+SS	Rye(Secale cereale L.)/black oats (Avena hirsutum L. strigosa Schreb)	Cotton (Gossypium hirsutum L.)	Corn (Zea mays L.)-cotton	Site Specific Evaluation
2	Shorter	AL	Coarse-loamy, siliceous, subactive, thermic Plinthic Paleudult	Compass	1989	CT/ NT+SS	rye	cotton	corn-cotton	Old Farming System
3	Tifton	GA	Fine-loamy, kaolinitic, thermic Plinthic Kandiudult	Tifton	1998	CT/ST	rye	Peanut (Arachis hypogaea L.)	cotton-peanut	Gibbs Farm, Cotton-Peanut Rotation
4	Watkinsville	GA	fine, kaolinitic, thermic Typic Kanhapludult	Cecil	1991	CT/NT	rye	corn	corn	Water Quality Poultry Litter
5	Watkinsville	GA	fine, kaolinitic, thermic Typic Kanhapludult	Cecil	1991	CT/NT	rye	corn	corn	Water Quality Conventional Fertilizer
6	Washington	MS	very-fine, smectitic, thermic Chromic Epiaquert	Sharkey	2001	CT/NT	none	Soybean (Glycine max (L.) Merr.)	soybean-rice (Oryza sativa L.)	Soybean-Rice Rotation
7	Centralia	MO	fine, smectitic, mesic Vertic Albaqualf	Adco	1991	CT/NT	none	corn	corn-soybean	Summit ACS2
8	Florence	SC	fine-loamy, kaolinitic, thermic Typic Kandiudult	Norfolk	1979	CT/ NT+SS	rye	soybean	corn- soybean	Long-term Conservation
9	Jackson	TN	Fine-silty, mixed, active, thermic Ultic Hapludalfs	Lexington	1979	CT/NT		soybean	soybean	Long-term Soybean
10	Bushland	TX	fine, mixed, superactive, thermic, Torrertic Paleustoll	Pullman	1995	SM/NT	fallow	wheat	wheat-sorghum [Sorghum bicolor (L.) Moench]-fallow	Level Terraces
11	Temple	TX	fine-silty, carbonatic, thermic Udorthentic Haplustoll	Austin	2001	SM/NP	fallow	wheat	wheat-corn	Old Prairie

† Tillage abbreviations: CT– Conventional tillage (varies primarily chisel plowing or moldboard followed by disking); NT+SS– No-tillage with non-inversion deep tillage; NT– No-Tillage; NP– Not plowed (prairie soil); ST– Strip tillage (in-row subsoil unit for disruption of subsurface pan and coulters for preparation of narrow strip of tilled soil); SM– Stubble mulch tillage (sweeps to undercut weeds).

borate buffer (pH = 11.2) to obtain 40 mL of distillate, and the $NH_4–N$ content determined as in the NaOH_N procedure.

Short-Term Anaerobic Incubation

Ammonium released during anaerobic incubation was determined following the method of Keeney and Bremner (1966). A 5-g soil sample was placed in a 16×150 mm (outer size) screw capped test tube, and 12.5 mL of water added to limit headspace inside the test tube. Caps were securely fastened to ensure anaerobic conditions. After 7 d of incubation at 40°C, samples were transferred to a 50-mL centrifuge tube by rinsing with 12.5 mL of 4 mol L^{-1} KCl. Samples were shaken 30 min on a horizontal reciprocating shaker, filtered through a Whatman No. 42 filter paper, and extracts were frozen until analysis for $NH_4–N$. The amount of N mineralized during the 7-d incubation was calculated by subtracting Cold_NH_4.

Three Day Flush of Carbon Dioxide

The CO_2 released from soil during a 3-d incubation was determined by the procedure of Franzluebbers et al. (2000). Soils (40 g) were weighed into a 60-mL glass vial, and adjusted to 50% water-filled pore space. Soils were incubated at 25°C inside a 1-L wide-mouth canning jar with a vial of water (10 mL) and a vial with 10 mL of 1 mol L^{-1} NaOH (for capturing CO_2). Jars were sealed with a screw cap lid. The quantity of CO_2 evolved was determined by back-titrating excess NaOH with 1.0 mol L^{-1} HCl after addition of $BaCl_2$ to precipitate carbonate (Anderson, 1982). Jars incubated with no soil were used to estimate background CO_2 concentration and results were expressed as mg C kg^{-1} soil.

Nitrogen Mineralization Over 24 Days

Soils from the 3-d flush of CO_2 were incubated for an additional 21 d to determine short-term potentially mineralizable N (Nmin_24), as suggested by Franzluebbers et al. (2000). The jars were opened two to three times a week to ensure sufficient oxygen. Soils were dried at 60°C, and the amount of $NO_3–N$ and $NH_4–N$ mineralized determined as described above for the long-term incubation study. The amount of N mineralized was calculated by subtracting initial $NO_3–N$ and $NH_4–N$.

Calcium Hypochlorite Oxidation

Organic matter oxidized by addition of calcium hypochlorite $[Ca(OCl)_2]$ to a soil–water infusion (5 g soil + 5 mL of water) was measured as the change in pressure inside a sealed 120-mL serum bottle as described by Picone et al. (2002). We investigated this procedure because it is simple, low cost, and has been shown to be related to total organic matter content, potentially mineralizable N, and the capacity of the soil to evolve CO_2 (Picone et al., 2002).

Statistical Analysis

All statistical analyses were conducted using version 9.2 of SAS (SAS Institute Inc., 2008). Normality of data was assessed using the UNIVARIATE procedure. Values of N_0, N_0^*, k, and all N indices were log transformed to normalize the data for the remaining statistical procedures. Correlations among indices, and between indices and N_0, N_0^*, or k were determined with the CORR procedure. Linear relationships between the indi-

ces and N_0, N_0^*, or k were evaluated using the ROBUSTREG procedure. The stepwise method of the REG procedure was used to determine the best combination of indices for predicting N_0, N_0^*, or k. A significance level of $\alpha = 0.05$ was used in all cases.

RESULTS AND DISCUSSION

Soil physical and chemical properties are presented in Table 3 and are typical representatives of the weathered soils of the South. Soil textures ranged from sand to clay, with most being loams. Soil pH ranged from 4.8 in the 5- to 15-cm layer of the Cecil soil to 8.0 for the 5- to 15-cm layer of the Austin soil (Table 3). Similar ranges in values were determined for C, N, POMC, and POMN (Table 4). Maximum values of C, N, POMC, and POMN were 44.9, 3.3, 22.4, and 1.4 g kg^{-1}, respectively, for the Austin soil while minimum values of 3.6, 0.2, 1.1, and 0.03 g kg^{-1}, respectively, were determined for the Tifton soil (see Table 2 for soil descriptions).

Broad ranges in values were also observed for extractable or distillable N. Maximum values for Cold_N, Hot_N, Hyd_N, NaOH_N, and PB_N were 31.8, 35.4, 27.3, 453.5, and 59.9 mg kg^{-1}, respectively, while minimum values were 0.1, 2.9, 2.0, 33.0, and 7.0 mg kg^{-1}, respectively. Mean values for these methods were 4.1, 10.6, 8.1, 155.5, and 29.3 mg kg^{-1}, respectively. Comparing means among these methods indicates they identify different N pools with a progression of Cold_N < Hot_N = Hyd_N < PB_N < NaOH_N. The Cold_N represents the inorganic N fraction, while the Hot_N and Hyd_N includes easily decomposable organic matter while the PB_N and NaOH_N (distilled N) fractions are probably derived from these fractions along with other more resistant but hydrolyzable unidentified N fractions (Greenfield, 2001). Among these procedures, NaOH_N is the most aggressive representing on average 14% of TN, while Cold_N and Hyd_N represented only 0.4 and 0.7% of TN, respectively.

Correlation coefficients among methods were significant with several having r values greater than 0.90 (Table 5). Biological methods (Ana_N, Nmin_24, and Fl_CO$_2$) had stronger associations with C, N, POMC, and POMN than chemical methods. Correlations among chemical methods were similar to correlations between chemical and biological methods (Table 5). Biological methods generally had stronger associations with each other ($r = 0.86$ to 0.91) than with the chemical methods ($r = 0.60$ to 0.94). Of the chemical methods, Hot_N and Hyd_N (estimated from the same procedure) had the strongest association with the biological methods and with C, N, POMC, and POMN with r values > 0.80. In contrast to our results, Soon et al. (2007) found that the chemical methods Hot_N and Hyd_N were more strongly correlated with soil organic C and TN than were the biological indicators aerobic mineralizable N and Ana_N.

Potentially mineralizable N, as evaluated by Ana_N, is listed as one of the key biological indicators of soil quality by Doran and Parkin (1994) and has been used by several authors for comparison with more rapid laboratory N mineralization indices,

Table 3. Physical and chemical properties of soils used in evaluation of N mineralization indices.

ID	Soil series	Tillage†	Depth	Sand	Silt	Clay	pH	P	K	Ca	Mg
			cm		—%—				—kg ha^{-1}—		
1	Bama	CT	0–5	56	37	7	6.9	127	289	1680	361
1	Bama	CT	5–15	54	41	5	6.9	92	209	1565	352
1	Bama	NT+SS	0–5	56	40	5	6.7	140	244	2153	458
1	Bama	NT+SS	5–15	55	35	10	6.8	45	191	1434	333
2	Compass	CT	0–5	79	20	1	6.3	67	167	876	104
2	Compass	CT	5–15	79	20	0	6.4	45	96	863	89
2	Compass	NT+SS	0–5	80	19	0	6.5	59	116	1081	144
2	Compass	NT+SS	5–15	82	18	0	5.8	64	70	603	65
3	Tifton	CT	0–5	87	12	1	6.1	57	135	541	48
3	Tifton	CT	5–15	85	12	3	5.5	42	77	268	19
3	Tifton	ST	0–5	90	9	1	6.5	91	172	1201	98
3	Tifton	ST	5–15	91	8	1	6.2	57	100	507	37
4	Cecil	CT	0–5	73	24	3	5.9	337	290	1387	168
4	Cecil	CT	5–15	72	25	4	6.0	319	315	1497	176
4	Cecil	NT	0–5	76	19	6	5.9	575	278	3056	298
4	Cecil	NT	5–15	75	21	4	5.7	112	163	590	88
5	Cecil	CT	0–5	70	24	5	5.0	74	163	500	71
5	Cecil	CT	5–15	67	26	7	4.8	52	132	465	58
5	Cecil	NT	0–5	75	21	4	5.6	99	191	2221	203
5	Cecil	NT	5–15	75	21	4	4.8	36	89	322	29
6	Sharkey	CT	0–5	5	53	42	6.5	60	355	5426	1257
6	Sharkey	CT	5–15	4	52	44	6.4	51	363	5440	1277
6	Sharkey	NT	0–5	5	54	41	6.4	48	445	4931	1131
6	Sharkey	NT	5–15	4	54	42	6.6	57	420	5468	1238
7	Adco	CT	0–5	8	78	14	7.3	137	209	4853	374
7	Adco	CT	5–15	6	79	15	6.7	32	128	3357	259
7	Adco	NT	0–5	8	77	16	7.3	128	207	5727	400
7	Adco	NT	5–15	6	78	16	7.0	32	132	3877	300
8	Norfolk	CT	0–5	73	25	2	6.4	24	307	861	158
8	Norfolk	CT	5–15	73	25	2	6.3	19	153	861	130
8	Norfolk	NT+SS	0–5	76	23	1	6.9	106	249	3230	632
8	Norfolk	NT+SS	5–15	75	23	1	6.7	72	102	967	150
9	Lexington	CT	0–5	10	79	11	6.7	33	99	2891	199
9	Lexington	CT	5–15	7	79	14	6.5	32	106	2193	197
9	Lexington	NT	0–5	12	78	11	7.0	37	161	8903	253
9	Lexington	NT	5–15	9	79	12	7.2	40	165	5015	299
10	Pullman	NT	0–5	21	52	27	6.4	132	661	3277	620
10	Pullman	NT	5–15	18	51	32	6.7	93	554	3652	652
10	Pullman	SM	0–5	21	50	29	6.6	98	626	3676	661
10	Pullman	SM	5–15	19	49	31	6.6	76	440	3023	537
11	Austin	SM	0–5	10	49	41	7.9	7	168	47544	130
11	Austin	SM	5–15	10	50	40	8.0	5	136	47544	112
11	Austin	NP	0–5	8	45	46	7.7	10	257	47544	233
11	Austin	NP	5–15	7	41	53	7.8	9	150	47544	197

† Tillage abbreviations as in Table 2.

Table 4. Results from various indices‡ of potentially mineralizable N for several soils and N_0, N_0^*, and k determined from long-term incubation data.

ID	Soil series	Tillage‡	Depth	TC	TN	POMC	POMN	Ana_N	Cold_N	Hot_N	Hyd_N	NaOH_N	PB_N	Nmin_24	Fl_CO2	Ca_hypcl	N_0	k	N_0^*
			cm	g kg⁻¹	mg kg⁻¹	g kg⁻¹	g kg⁻¹					mg kg⁻¹				kPa	mg kg⁻¹	wk⁻¹	mg kg⁻¹
1	Bama	CT	0–5	12.6	933	4.6	217.3	35.4	2.9	9.5	7.6	119.6	23.5	19.7	145.2	6.3	189	0.060	197
1	Bama	CT	5–15	8.9	721	3.2	122.1	19.4	1.4	7.0	5.5	102.5	16.7	15.2	79.6	5.0	147	0.045	134
1	Bama	NT+SS	0–5	22.2	1661	15.9	770.2	78.3	10.5	20.3	15.2	222.9	41.5	61.5	337.7	10.9	284	0.174	396
1	Bama	NT+SS	5–15	7.1	628	1.9	71.3	15.4	1.8	6.6	5.0	71.6	17.1	12.8	59.2	3.6	114	0.044	103
2	Compass	CT	0–5	7.6	645	2.3	21.7	22.1	1.5	6.1	4.6	76.0	16.0	15.3	115.7	4.1	105	0.171	151
2	Compass	CT	5–15	5.4	319	1.1	54.4	5.7	0.7	3.2	2.6	55.5	9.5	6.0	36.9	3.0	58	0.070	65
2	Compass	NT+SS	0–5	10.1	783	2.9	137.9	21.7	1.9	8.6	6.7	105.9	21.7	16.8	118.6	5.0	113	0.132	150
2	Compass	NT+SS	5–15	4.8	303	0.9	48.6	4.3	0.8	3.5	2.5	47.1	9.4	5.4	37.4	3.3	64	0.031	47
3	Tifton	CT	0–5	4.9	354	1.3	110.8	12.7	0.1	4.5	2.8	48.1	10.7	5.7	83.7	2.8	42	0.106	53
3	Tifton	CT	5–15	4.4	339	1.3	75.5	9.2	0.1	4.1	2.6	52.1	10.6	4.7	44.4	3.1	35	0.063	38
3	Tifton	ST	0–5	6.5	535	2.8	175.2	21.1	0.4	6.6	4.1	62.8	13.5	9.5	84.4	3.6	119	0.060	125
3	Tifton	ST	5–15	3.6	223	1.1	32.6	6.8	0.3	2.9	2.0	33.0	7.0	3.5	54.6	2.8	43	0.036	35
4	Cecil	CT	0–5	17.6	1523	6.7	500.8	73.7	7.5	18.4	15.1	164.6	40.8	47.2	288.7	11.2	456	0.058	470
4	Cecil	CT	5–15	11.1	1095	3.7	260.0	44.4	3.9	12.8	10.7	143.9	30.8	27.7	206.2	6.7	283	0.051	276
4	Cecil	NT	0–5	34.2	2970	18.9	1187.2	86.1	18.1	35.4	27.3	311.7	59.9	95.4	339.1	11.9	488	0.133	649
4	Cecil	NT	5–15	7.2	697	0.9	50.8	20.6	1.7	6.8	5.0	106.6	19.6	15.8	79.1	4.2	126	0.046	117
5	Cecil	CT	0–5	11.4	855	5.1	271.1	30.0	1.5	13.8	10.2	170.2	34.2	24.3	196.9	8.6	192	0.085	228
5	Cecil	CT	5–15	9.7	830	2.6	139.0	11.6	0.4	5.6	3.7	152.7	27.6	9.4	83.3	5.9	167	0.038	139
5	Cecil	NT	0–5	26.1	1975	16.3	979.5	55.1	2.2	21.7	17.9	249.5	53.1	45.7	231.4	13.7	274	0.090	330
5	Cecil	NT	5–15	7.4	586	1.2	78.0	8.1	0.3	7.2	5.7	127.4	19.0	10.5	64.0	4.8	71	0.074	81
6	Sharkey	CT	0–5	14.1	1439	2.9	112.0	32.9	1.7	11.7	8.3	221.4	44.1	18.0	148.8	9.6	dnc§	dnc	105
6	Sharkey	CT	5–15	14.1	1324	1.8	99.1	38.9	0.9	12.1	8.8	172.0	38.4	14.2	109.2	9.3	dnc	dnc	93
6	Sharkey	NT	0–5	17.3	1638	4.0	200.7	51.1	0.8	16.2	10.3	240.1	56.0	27.7	196.9	10.3	316	0.023	188
6	Sharkey	NT	5–15	15.1	1526	2.1	104.1	37.9	0.4	13.6	8.7	240.5	48.2	17.7	127.7	10.3	dnc	dnc	85
7	Adco	CT	0–5	14.1	1338	4.7	285.7	44.0	0.8	11.5	9.7	198.1	49.0	20.8	124.5	9.4	175	0.069	195
7	Adco	CT	5–15	10.0	961	1.1	56.9	10.9	1.1	7.8	6.7	185.9	49.6	7.5	75.2	6.0	151	0.023	89
7	Adco	NT	0–5	17.3	1587	6.5	307.4	46.3	1.0	12.4	10.8	233.2	51.0	21.6	155.0	10.0	203	0.070	227
7	Adco	NT	5–15	10.8	1060	1.4	86.0	19.0	1.0	9.0	7.7	158.9	42.5	12.5	69.9	5.5	86	0.107	112
8	Norfolk	CT	0–5	7.6	536	2.4	159.0	25.9	9.0	7.0	4.8	111.9	20.8	16.6	141.2	4.8	117	0.099	147
8	Norfolk	CT	5–15	6.6	536	2.3	147.4	21.5	4.7	5.3	4.3	89.0	13.8	11.7	62.6	4.2	103	0.055	104
8	Norfolk	NT+SS	0–5	22.9	1703	12.7	729.1	40.5	31.8	17.0	13.3	279.2	37.9	34.6	192.5	13.5	294	0.064	316
8	Norfolk	NT+SS	5–15	5.2	382	1.2	102.4	7.4	2.8	4.2	3.1	96.9	12.6	7.4	28.0	3.4	47	0.093	58
9	Lexington	CT	0–5	10.9	1115	2.7	139.2	47.9	9.6	10.9	9.7	132.0	32.3	22.1	77.1	5.7	219	0.060	230
9	Lexington	CT	5–15	5.0	668	1.1	53.7	7.1	2.0	5.4	4.3	99.6	22.1	7.9	34.4	3.2	46	0.088	56

Table 4 Continued.

ID	Soil series	Tillage‡	Depth	TC	TN	POMC	POMN	Ana_N	Cold_N	Hot_N	Hyd_N	NaOH_N	PB_N	Nmin_24	Fl_CO2	Ca_hypcl	N_0	k	N_0*
			cm	g kg⁻¹	mg kg⁻¹	g kg⁻¹					mg kg⁻¹					kPa	mg kg⁻¹	wk⁻¹	mg kg⁻¹
9	Lexington	NT	0–5	18.4	1611	5.7	308.5	67.2	15.4	18.3	15.5	229.1	45.5	49.8	171.8	11.3	266	0.088	319
9	Lexington	NT	5–15	5.4	717	0.7	34.6	11.5	2.5	7.6	6.3	113.7	21.7	9.8	45.5	3.6	54	0.103	68
10	Pullman	NT	0–5	11.9	1128	3.7	228.3	25.8	2.9	7.7	6.2	128.3	28.8	17.5	82.2	8.6	281	0.036	228
10	Pullman	NT	5–15	8.6	838	1.2	89.5	6.9	1.2	5.7	4.3	134.2	23.0	8.7	32.0	5.2	67	0.062	72
10	Pullman	SM	0–5	9.5	971	2.0	135.4	27.7	2.2	8.4	5.5	130.2	28.5	12.9	69.1	6.1	379	0.018	188
10	Pullman	SM	5–15	8.7	1003	1.0	79.2	12.4	1.4	7.4	5.6	149.4	25.6	9.7	46.2	5.8	147	0.039	121
11	Austin	SM	0–5	18.0	1564	4.7	316.0	31.0	4.9	11.6	8.2	142.3	19.4	31.0	119.0	8.0	dnc	dnc	142
11	Austin	SM	5–15	14.6	1173	1.8	114.4	12.5	1.6	7.8	5.6	96.9	13.5	22.0	57.9	4.9	dnc	dnc	77
11	Austin	NP	0–5	44.9	3296	22.4	1473.1	115.7	13.0	26.5	21.0	453.5	50.3	116.4	310.0	9.1	454	0.057	465
11	Austin	NP	5–15	28.2	2464	5.2	373.4	71.6	8.6	16.8	12.6	383.0	32.8	69.0	199.9	9.6	dnc	dnc	199
	Mean			12.8	1103	4.3	251	31.7	4.1	10.6	8.1	155.5	29.3	23.6	121.9	6.8	178	0.07	183¶

† Abbreviations for methods as in Table 1.

‡ Tillage abbreviations as in Table 2.

§ dnc indicates where the single exponential failed to converge.

¶ For soils where dnc is indicated for N_0 the values of N_0* were not included in the overall N_0* mean.

and for soil management effects (Bushong et al., 2007, 2008; Soon et al., 2007). It is a more standardized, simpler, and quicker procedure than the long-term aerobic incubation procedure. In our evaluations, Ana_N was strongly and positively correlated with Hot_N, Hyd_N, Nmin_24, and Fl_CO₂. Soon et al. (2007) also found a strong correlation between Nmin_24 and Ana_N (r = 0.90). Several authors have suggested the 7-d anaerobic incubation is the best biological indicator of potentially available N (Bushong et al., 2007, 2008; Soon et al., 2007).

Values of N_0 determined with the single exponential equation for each soil-tillage-depth combination ranged from 35 mg N kg⁻¹ soil for the 5- to 15-cm depth of the conventionally tilled Tifton soil to 488 mg N kg⁻¹ soil for the 5- to 15-cm depth of the no-till Cecil soil having a long history of poultry litter application (Table 4). Values for N_0 and k could not be determined for three out of the four treatments of the Sharkey and Austin soils because the exponential equation did not fit the observations. Cumulative mineralized N declined later in the incubation for treatments that failed to converge which indicated possible N losses due to denitrification. The range of values observed for N_0 is similar to other reports in the literature [Curtin and Wen, 1999 (71 to 630 mg kg⁻¹); Jalil et al., 1996 (71 to 278 mg kg⁻¹)]. Sharifi et al. (2007) recently reported a range of 54 to 197 mg N kg⁻¹ soil for 153 samples from 17 field studies in New Brunswick, Quebec, Manitoba, and Saskatchewan, Canada, and Maine, USA. The average value for N_0 for our soils was 178 mg N kg⁻¹ soil. Values of k ranged from 0.018 wk⁻¹ for the 5- to 15-cm depth of the Pullman soil in stubble mulch tillage to 0.174 wk⁻¹ for the 0- to 5-cm depth of the Bama soil in no-till with non-inversion deep tillage. The average k for all soils was 0.070 wk⁻¹. This is similar to the average k of 0.054 wk⁻¹ reported by Stanford and Smith (1972) for several U.S. soils, 0.067 wk⁻¹ for 42 soils from the Saskatchewan province reported by Jalil et al. (1996) and 0.080 wk⁻¹ reported by Curtin and Wen (1999). Other authors have observed that k values exhibited a wide range over soils (Juma et al., 1984; Paustian and Bonde 1987; Dendooven et al., 1995; Wang et al., 2003; Sharifi et al., 2007).

Using the approach of Wang et al. (2003) to determine N_0* with a fixed k (0.054 wk⁻¹) produced slightly greater values compared with N_0. The average value of N_0* was 183 mg N kg⁻¹ soil, and ranged from 35 to 649 mg N kg⁻¹ soil. Within a location, the values of N_0 and N_0* were very close. In general, greater amounts of potentially mineralizable N were found in minimum tillage systems compared with conventional tillage systems, and for surface soil compared with subsurface soil. The contrast between surface and subsurface soil was usually greater with N_0* compared with N_0. One consequence of fitting N_0* with a fixed k is that it allowed the exponential model to converge for all treatments including those from the Austin and Sharkey soils (Table 4). Although the fit of the model was not good in these cases, the resulting estimates of N_0* were consistent with results for the other soils as to differences between management and soil depth. Wang et al. (2003) cautioned that N_0* estimated with a fixed k does not represent a discrete and homogeneous pool of similar chemical forms of organic N, but they suggest it provides a reliable benchmark to allow comparison of N mineralization capacity between different soils.

Table 5. Pearson correlation coefficients (*r*) indicating association between laboratory methods.

	C†	N	POMC	POMN	Cold_N	Hot_N	Hyd_N	NaOH_N	PB_N	Ana_N	Nmin_24	Fl_CO2
N	0.959‡											
POMC	0.857	0.750										
POMN	0.844	0.748	0.932									
Cold_N	0.609	0.598	0.604	0.591								
Hot_N	0.936	0.937	0.836	0.822	0.622							
Hyd_N	0.925	0.933	0.822	0.805	0.665	0.988						
NaOH_N	0.899	0.937	0.681	0.709	0.572	0.888	0.888					
PB_N	0.807	0.882	0.617	0.616	0.448	0.865	0.873	0.918				
Ana_N	0.862	0.841	0.848	0.799	0.604	0.913	0.894	0.764	0.755			
Nmin_24	0.930	0.890	0.876	0.845	0.744	0.935	0.931	0.815	0.710	0.907		
Fl_CO2	0.826	0.749	0.876	0.795	0.504	0.876	0.846	0.699	0.694	0.912	0.863	
Ca_hypcl	0.888	0.858	0.812	0.795	0.515	0.891	0.877	0.845	0.836	0.810	0.801	0.807

† Abbreviations as in Table 1.

‡ All correlations significant at *P* < 0.001 except for PB_N vs. Cold_N, which was significant at *P* = 0.002.

Correlations between N_0 and the N mineralization methods were variable ranging from 0.615 to 0.887 (Fig. 1). Figure 1 shows that the association of N_0 with several indices is good for most soils. The strongest correlations with N_0 were with total C and N, Ana_N, Hot_N, and Nmin_24. Total C and N can be determined in a relatively short period of time, while Hot_N and Hyd_N require a 4-h incubation. Longer periods of time are required to determine Ana_N and Nmin_24, but they may be more reliable (Table 5 and Fig. 1B). Soon et al. (2007) reported lower coefficients of variation for Ana_N and Nmin_24 compared with other methods. Weighted least square regressions indicated these methods explained 60 to 65% of the variation in N_0 (Table 6). Somewhat lower correlations and fits of regressions were found for the other N indices; however, most had correlations above *r* = 0.75 (Fig. 1) and weighted least square regression coefficients with r^2 > 0.50 (Table 6).

Gianello and Bremner (1986a, 1986b, 1988) proposed Hot_N and PB_N as two methods to predict N_0. Jalil et al. (1996) reported r^2 values of 0.54, 0.48, 0.78, and 0.73 for linear regressions of N_0 with organic N, Hot_N, Hyd_N, and PB_N, respectively. Clay and Malzer (1993) found that PB_N more accurately reflected changes in mineralizable N and N availability to soybean (*Glycine max* L. Merr.) over time compared with Hot_N. Sharifi et al. (2007) found the correlations for PB_N and Hot_N with N_0 were not significant, which was similar to the lower correlation found by Curtin and Wen (1999). Curtin and Wen (1999) also reported that Hot_N was poorly correlated with N_0 (*r* = 0.36, *P* < 0.01), but it was reasonably well related to N mineralized in the first 2 wk of incubation (*r* = 0.80, *P* < 0.001). Our results for Hot_N and PB_N indicated a much stronger relationship with N_0 compared with the results of Sharifi et al. (2007) and Curtin and Wen (1999). Unlike Jalil et al. (1996) and Curtin and Wen (1999), who found improved predictions of N_0 with Hyd_N (not corrected for the initial NH_4–N concentration), our results indicate that Hot_N and Hyd_N produce similar predictions of N_0 (Table 6). The strong association between N_0 and Nmin_24 supports other research indicating that short term aerobic incubations may be useful for indicating N availability in soils (Franzluebbers, 1999; Franzluebbers et al., 2000; Soon et al., 2007). Data from Stanford and Smith (1972), Smith et al. (1994), and Jalil et al. (1996) indicate that short-term (14 d) N mineralization is highly related (r^2 = 0.80

± 0.05) to net N mineralization during 168 to 210 d. Soon et al. (2007) demonstrated that Nmin_24 and Ana_N were more sensitive to tillage, liming, and crop sequences compared to Hot_N or Hyd_N, especially when using 5-cm deep soils.

Correlations between *k* and the N indices were poor, and only significant for C and N (Fig. 1). Linear regression results were similar to the correlation results in that none of the indices were good predictors of *k* using linear regression (Table 6). In contrast to our results, Curtin and Wen (1999) found significant (*P* < 0.001) positive relationships between *k* and Hot_N (r^2 = 0.56) and PB_N (r^2 = 0.37, *P* < 0.001). Other authors have reported poor association between various indices and *k*. It is not surprising that *k* would be poorly correlated with any of the indices since these indices predominantly measure various fractions of the N pool and *k* is an indication of the susceptibility of these pools to microbial activity. Estimation of *k* is problematic because it is very sensitive to variation in the dataset. In a Monte Carlo simulation, even small (1 –2%) amounts of random variation have been shown to result in greater variation in estimates of *k* even when the underlying function was in fact exponential (Fisher et al., 1989). Use of a single exponential model in field studies is a simplification, and the logistics of determining data for each point within 1 or 2% generally prevents estimation of *k* with high precision (Schomberg and Cabrera, 2001; Schomberg et al., 2006). Even with this caveat, it appears that *k* may be less variable compared with N_0 across a wide range of soils as indicated by Stanford and Smith (1972) and reflected in our data and the data of Curtin and Wen (1999) and Jalil et al. (1996). Wang et al. (2003) showed that changes in N_0 and *k* were often inversely related, and were a function of the nonlinear iterative fitting process as well as the length of incubation. These factors led to their evaluation of using a standard *k* for determining N_0, which more accurately reflected soil conditions compared with simultaneous fitting N_0 and *k*. If *k* determined under standard conditions falls within a narrow range for most soils as indicated by many papers in the literature, then there would be little reason to expect it to be correlated to the various indices, and the use of a standard *k* could help in promoting the estimation of potential N mineralization by soil testing laboratories.

Correlations between N_0* and the N mineralization indices were better than those between N_0 and the indices (Fig. 1). Correlations ranged from 0.71 to 0.95 with the best correlations
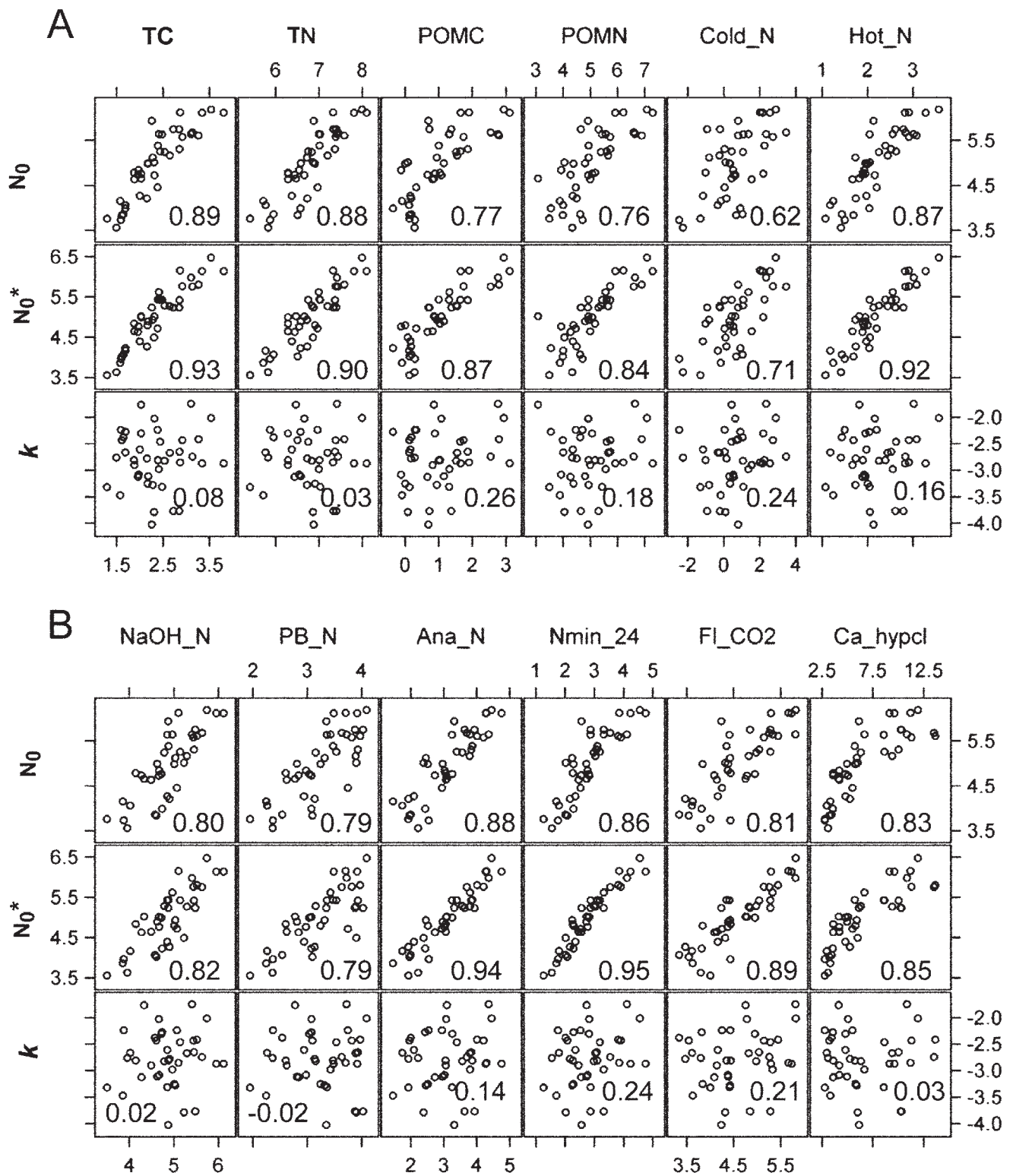
Fig. 1. Scatter plots indicating associations for laboratory N indices† with N_0, N_0^*, and k. Hyd_N is not included in the plot matrix because it was nearly identical to Hot_N. Value in each plot is the Person correlation coefficient. Correlations between the N indices and N_0 or N_0^* were significant at $P < 0.001$ while correlations between the N indices and k were not significant at $P < 0.05$. Abbreviations as in Table 1. Units for C and POMC are log(g kg^{-1}). Units for N, POMN, Cold_N, Hot_N, NaOH_N, PB_N, Ana_N, Nmin_24, Fl_CO2, N_0 and N_0^* are log(mg kg^{-1}). Unit for Ca_hypcl is log(kPa) and for k is log(wk^{-1}).

being with Nmin_24, Ana_N, total C, and Hot_N (same as with N_0). Examining Fig. 1 shows the closer alignment of data along the 1 to 1 line for N_0^* compared with N_0. Prediction of N_0^* with the N indices using linear regression resulted in coefficients of determination ranging from 0.46 to 0.82 (Table 6).

The best predictor of N_0^* was Nmin_24, which described 82% of the variation in N_0^*. Other indices resulting in good linear regressions with N_0^* were Ana_N, total C, and Hot_N. Cold_N was the poorest estimator of N_0^* with an $r^2 = 0.46$.

Table 6. Equations† for predicting N_0, N_0^*, and k from N indices.

	N index	Intercept	Standard error‡	Slope	Standard error	WLS r^2§
N_0¶	TC	2.36	0.23	1.12	0.09	0.65
	TN	−2.15	0.63	1.05	0.09	0.64
	POMC	4.33	0.12	0.64	0.08	0.52
	POMN	2.11	0.41	0.57	0.08	0.50
	Cold_N	4.77	0.11	0.34	0.07	0.35
	Hot_N	2.58	0.23	1.10	0.10	0.62
	Hyd_N	3.05	0.21	1.01	0.10	0.60
	NaOH_N	−0.02	0.60	1.03	0.12	0.55
	PB_N	1.60	0.43	1.05	0.13	0.54
	Ana_N	2.54	0.22	0.78	0.07	0.63
	Nmin_24	2.71	0.20	0.80	0.07	0.62
	Fl_CO2	0.78	0.43	0.91	0.09	0.58
	Ca_hypcl	3.69	0.16	0.19	0.02	0.57
N_0^*	C	2.32	0.18	1.14	0.08	0.75
	N	−2.12	0.57	1.05	0.08	0.69
	POMC	4.27	0.09	0.70	0.06	0.65
	POMN	1.52	0.31	0.69	0.06	0.64
	Cold_N	4.76	0.09	0.39	0.06	0.46
	Hot_N	2.49	0.17	1.15	0.08	0.77
	Hyd_N	2.97	0.14	1.07	0.07	0.65
	NaOH_N	0.02	0.57	1.02	0.12	0.60
	PB_N	1.71	0.42	1.01	0.13	0.57
	Ana_N	2.45	0.16	0.81	0.05	0.75
	Nmin_24	2.60	0.13	0.85	0.04	0.82
	Fl_CO2	0.88	0.31	0.91	0.07	0.64
	Ca_hypcl	3.70	0.15	0.19	0.02	0.66
k	TC	−2.96	0.35	0.07	0.15	0.01
	TN	−2.98	0.94	0.03	0.14	0.00
	POMC	−2.95	0.13	0.15	0.09	0.05
	POMN	−3.27	0.44	0.09	0.09	0.03
	Cold_N	−2.85	0.09	0.10	0.06	0.04
	Hot_N	−3.11	0.33	0.14	0.15	0.03
	Hyd_N	−3.11	0.27	0.16	0.14	0.04
	NaOH_N	−2.87	0.72	0.01	0.15	0.00
	PB_N	−2.74	0.50	−0.02	0.15	0.00
	Ana_N	−3.08	0.33	0.09	0.10	0.02
	Nmin_24	−3.23	0.30	0.15	0.10	0.04
	Fl_CO2	−3.53	0.57	0.16	0.12	0.03
	Ca_hypcl	−2.83	0.20	0.01	0.03	0.00

† Equations are Y = Intercept + slope (x) where x is the measured N index, and the intercept and slope were estimated by regression.

‡ Std Error is the standard error of the estimate.

§ WLS r^2 is a weighted least squares estimate of r^2 from ROBUSTREG adjusted for outliers.

¶ All slopes and intercepts for predicting N_0 and N_0^* were significant at $P < 0.001$. All intercepts for predicting k were significant at $P < 0.001$. Slopes for predicting k from N, Hot_N, Hyd_N, Ana_N, and Nmin_24 were significant at $P < 0.05$. All other slopes for k were not significant.

Gallagher and Bartholomew (1964) found that predictions of N availability were improved when N test methods and soil properties were combined in multiple regressions. We used the stepwise selection method in the REG procedure to select the best combination of N indices for predicting N_0, N_0^*, and k. This purely empirical approach does not restrict the resulting equations to any hierarchical combination of methods based on organic matter fractions. The results may therefore not have a simple biological basis for interpretation, but could still be useful in establishing laboratory procedures for N recommendations.

The best combination of methods to estimate N_0 was TN and Fl_CO2 (Table 7). Total N represents the total pool of N in the soil, and contains the mineralizable organic N as well as the more recalcitrant fraction of organic N while Fl_CO2 has been related to microbial biomass and mineralizable C and N in soils under different environments (Franzluebbers et al., 2000, 2001). The CO_2 released in the Fl_CO2 procedure reflects both (i) microbial population dynamics, [growth in response to release of metabolites due to drying and osmotic shock following rewetting (Jenkinson, 1966, Sorensen, 1974, Kieft et al., 1987)], and (ii) the steady-state rate of C mineralization reflecting the mineralizability of organic matter. Measurement of Fl_CO2 is relatively fast (i.e., 0–3 d) and sensitive, since 8 to 12 times more C than N is mineralized from soil organic matter.

The stepwise regression procedure identified a larger group of indices for prediction of N_0^* compared to N_0 (Table 7). The group included TN, Cold_N, NaOH_N, and Fl_CO2, and had an R^2 of 0.94. Total N and Fl_CO2 were indices selected for prediction of N_0. Addition of Cold_N and NaOH_N produces an interesting set of predictors. Cold_N is the mineral N pool initially present, and readily available to microorganisms on rewetting of the soil while NaOH_N measures the most chemically resistant but hydrolyzable N pool. On average NaOH_N represented 14% of TN, while Cold_N represented only 0.4% of TN in these soils. Wang and Li (1991) reported that predictions of plant N uptake in two pot experiments were significantly improved with inclusion of initial NO_3–N with NaOH-hydrolyzable N in regression equations (cited in Wang et al., 2001). Moreover, the correlation coefficients for NaOH-hydrolyzable N plus mineral N were much greater than those for the initial $(NH_4 + NO_3)$–N or TN (including NO_3–N). Wang et al. (2001) concluded that a test that integrates initial mineral N and NaOH-hydrolyzable organic N would be a better index than TN (including mineral N). With a multiple correlation coefficient of 0.94, the equation for N_0^* could be useful in estimating the size of the potentially mineralizable N pool for various soils particularly when modeling N cycling. Three of the four indices used in this equation are relatively fast to determine (<1 d) and Fl_CO2 takes only 3 d, which is much faster than a long-term incubation. These methods can also be determined using inexpensive equipment present in most laboratories (if TN is determined via Kjeldahl).

Prediction of k with a combination of N indices proved to be elusive (Table 7). The equation for the selected group of indices had a relatively low R^2 (0.36) indicating poor prediction value. This result was not unexpected, as noted above, due to the potential for k to be a characteristic mainly changing in response

Table 7. Multiple indices equations† for predicting N_0, N_0^*, and k.

Dependent	Variable	Parameter estimate	Standard error	Pr > |t|	95% Confidence limits		RMSE	Model R^2	Model Adj R^2
N_0	Intercept	−1.655	0.509	0.0025	−2.686	−0.623	0.288	0.86	0.85
	TN	0.682	0.114	0.0001	0.452	0.913			
	Fl_CO2	0.432	0.104	0.0002	0.221	0.642			
N_0^*	Intercept	−0.930	0.444	0.0436	−1.831	−0.028	0.185	0.94	0.94
	TN	0.820	0.178	0.0001	0.459	1.181			
	Cold_N	0.128	0.028	0.0001	0.072	0.185			
	NaOH_N	−0.336	0.167	0.0524	−0.676	0.004			
	Fl_CO2	0.421	0.071	0.0001	0.277	0.564			
k	Intercept	−3.563	0.390	< .0001	−4.356	−2.771	0.408	0.36	0.30
	TC	−1.380	0.373	0.0008	−2.139	−0.622			
	POMN	0.500	0.148	0.0019	0.199	0.802			

† Equations are constructed in the form $y = \beta_0 + x1\beta_1 + x2\beta_2 + x3\beta_3 + x4\beta_4$ where β_0 is the intercept, β_1, β_2, β_3, and β_4 are the parameter estimates and x1, x2, x3, and x4 are the measured N indices.

to physical influences and sensitivity in the fitting process. Many other authors have shown that it is difficult to identify a compositional factor that is predictive of k, which is why Wang et al. (2003) advocate use of a standardized k. Use of a standardized k that is modified due to climatic influences (temperature and water), as in many models, appears to be a logical approach for estimating N mineralization in most soils (Stanford and Smith, 1976; Campbell et al., 1997; Wang et al., 2003).

SUMMARY AND CONCLUSIONS

Our results indicate that a combination of laboratory methods can be useful for predicting potentially mineralizable N for a range of soils from the South, USA. The results should be applicable to other regions; however, combinations of indices may be slightly different due to types of clays and organic matter present in soils from other regions. We observed strong relationships between N_0 and the N indices total C and N, Ana_N, Nmin_24, Hot_N, and Hyd_N. Of these indices total C and N, Hot_N and Hyd_N are easy and quick to determine, while Ana_N and Nmin_24 require more time, but proved to have stronger relationships with N_0. Using a fixed value of k in estimating N_0^* improved the fit of relationships between the N indices and N_0^*. Combining indices in multiple regressions improved prediction of N_0 or N_0^* with the best equations having strong predictive potential ($R^2 = 0.86$ and 0.94, respectively). Combining TN and Fl_CO2 to predict N_0 and N_0^* relies on relatively simple methods, which are a logical combination of indices defining available substrate and microbial biomass. This particular combination could be easily adopted for predicting potential N availability over a range of soils and management conditions by soil testing laboratories and for modeling.

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