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Equations for Estimating the Amount of Nitrogen Mineralized from Crop Residues

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ABSTRACT

The amount of N mineralized or immobilized during the decomposition of a crop residue will influence the amount of N available for crop uptake and will ultimately impact N-management practices and groundwater quality. The objective of this work was to determine quantitative relationship(s) between a crop residue's chemical properties and the potential net amount of N that would mineralize in a season. Eight experiments (six from the literature and two conducted by the authors) were combined to determine general relationships between net N mineralized and residue chemical characteristics. Regression analysis indicated that 75 and 72% of the variability in the measured amounts of N mineralized in the eight experiments could be explained using either the C/N ratio or the square-root transformation of N concentration of the residue, respectively. The break point between net N mineralization and net immobilization was calculated to be at a C/N ratio of 40, which corresponds to a N concentration of about 10 g N/kg (assuming residue C is 400 g/kg). Eighty percent of the variability in the amount of N mineralized could be explained by a regression equation that included N and the lignin-to-N ratio as independent variables. The fitted equations provide estimates of the maximum amount of N that potentially will mineralize in a season from incorporated crop residues of different N contents.

THE N AVAILABILITY of a soil will change depending on the amount of N mineralized or immobilized during the decomposition of crop residues. Because no reliable laboratory method is available for accurately predicting these processes, fertilizer-recommendation procedures usually ignore or simply guess at the amount of N that will mineralize from decomposing crop residues. The problem lies in the complexity of organic-N turnover, which is influenced by variable residue and soil characteristics and various soil environmental factors (i.e., soil temperature, soil moisture, texture, etc.).

Because of the complexity of N mineralization, several researchers (Seligman and Van Kuelen, 1981; Seligman et al., 1986; White et al., 1988; Smith, 1979; Parnas, 1975; Molina et al., 1983) have used computer-simulation models as tools for learning more about the process of organic-N turnover. In most of these models, the C/N ratio, the N concentration of the residue, or both are used to control the N-mineralization rate (Seligman and Van Kuelen, 1981; Knapp et al., 1983; Smith, 1979; Parnas, 1975; Molina et al., 1983). However, good quantitative relationships between residue N concentration and N-mineralization amounts are lacking. General relationships are needed to predict the amount of N mineralized from a decomposing crop residue as a function of either the N concentration, C/N ratio, or some other easily measured chemical property of the residue. Harmsen and Van Schreven (1955) concluded that N concentrations of 15 to 20 g/kg (C/N ratios of 20–25) will consistently give net N mineralization, whereas at lower N concentrations net immobilization is expected. Alexander (1977) stated that the critical C/N ratio of a crop residue for net N mineralization to occur is less than 20 to 30, whereas C/N ratios wider than 30 favor net immobilization.

On the other hand, Muller et al. (1988) concluded that lignin concentration was better than N concentration and N concentration was better than C/N ratio in predicting the amount of N mineralized. This conclusion regarding lignin content was contrary to conclusions of other researchers (Iritani and Arnold, 1959; Millar et al., 1937; Frankenberger and Abdelmagid, 1985), who found lignin content less important than N concentration or C/N ratio.

From the above literature, it is evident that the best predictor of net N mineralization will vary with the experimental method used and the method of measuring the net effect (i.e., N uptake by a growing crop or periodic subsampling of incubated soil). Because methodology for determining net N mineralization varies and because of the insufficiency of single studies to develop a general relationship, our objective was to use data from several published studies along with our recent findings to develop a quantitative relationship between a crop residue's chemical composition and the amount of N mineralized.

MATERIALS AND METHODS

Eight experiments were selected, six from the literature and two from the authors' recent research. Some characteristics of the various experiments are listed in Table 1. Experiments with the following characteristics were selected: (i) laboratory experiments of at least 11 wk duration, done at 25 to 35 °C, under near-optimum soil moisture contents (incubations conducted under saturated conditions or with soils nearly air dry were not included), with mineral soils, using more than one crop residue with different N concentrations or C/N ratios; (ii) field experiments longer than 100 d.

The critical N factor, defined as the N concentration at which neither net N mineralization nor immobilization occurs, has been found in 4-wk incubations at 35 °C to be 16.6 to 20.0 g/kg (Iritani and Arnold, 1959). However, critical N factors as low as 8.0 g/kg can be calculated from data reported by Frankenberger and Abdelmagid (1985) (20-wk incubations at 23 °C). In general, when residues with N concentrations <5 g/kg are mixed with soil, net immobilization of N occurs. Because of this, residues with N concentrations <5 g/kg (C/N of 80) were not included in this analysis. Total residue C, N, and lignin for the studies conducted by the authors are given in Table 2. Chemical properties of the crop residues used in the other studies can be found in Frankenberger and Abdelmagid (1985), Fu et al. (1987), Jensen (1929), Millar et al. (1937), Van Schreven (1964), and Wagger et al. (1985).

For each experiment, the accumulated amount of N mineralized by the final sampling date was calculated as a percent of the amount applied in the residue. It was assumed that the amount of N mineralized by the final sampling date

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Table 1. Some characteristics of the studies analyzed.

Study†	Year reported	Soil series or description‡	Classification	Method	Time
W.T. Frankenberger	1985	Buren (sl)	fine-loamy, mixed, thermic Haplic Durixeralf	lab incubation leach tubes 28 °C	20
M.H. Fu	1988	Luther (l)	fine-loamy, mixed, mesic Aeric Ochraqualf	lab incubation leach tubes 30 °C	20
		Lester (sil)	fine-loamy, mixed, mesic Mollic Hapludalf		
		Nicollet (l)	fine-loamy, mixed, mesic Aquic Hapludoll		
H.L. Jensen	1929	loamy soil (l)		lab incubation destructive subsampling 25 °C	24
H.C. Millar	1937	Dickinson (sl)	coarse-loamy, mixed, mesic Typic Hapludoll	greenhouse pots destructive subsampling	11
D.A. Van Schreven	1964	heavy calcareous (l)		lab incubation 25 °C destructive sampling	16
M.F. Vigil (field study)	1989	Smolan (sl)	fine, montmorillonitic, mesic Pachic Argiustoll	field microplots ^{15}N-labeled sorghum residues	16
M.F. Vigil (lab study)	1989	Haynie (vfsl)	coarse-silty, mixed (calcareous), mesic Mollic Udifluvent	lab incubation leach tubes 35 °C	14
		Smolan (sil)	fine, montmorillonitic, mesic Pachic Argiustoll		
		Kahola (sil)	fine-silty, mixed, mesic Cumulic Hapludoll		
		Woodson (sic)	fine, montmorillonitic, thermic Abruptic Argiaquoll		
M.G. Wagger	1985	Haynie (vfsl)	coarse-silty, mixed (calcareous), mesic Mollic Udifluvent	Field microplots ^{15}N-labeled sorghum	44
		Kahola (sil)	fine-silty, mixed, mesic Cumulic Hapludoll		

† Each study is referenced by the first author.
‡ Letters in parentheses indicate soil texture: sl, sandy loam; l, loam; sil, silt loam; vfsl, very fine sandy loam; sic, silty clay.

Table 2. Selected chemical properties of the corp residues added to field microplots and used in laboratory incubations conducted by the authors.

Residue description	C/N	Total N	Total C	Total lignin
		g/kg		
Field study				
Stage 2 sorghum plants	20	21.0	411	51
Stage 3 sorghum plants	25	17.1	419	51
Postharvest sorghum leaves	30	13.3	404	71
Postharvest sorghum leaves	37	11.0	407	57
Stage 4 sorghum stems	27	15.3	411	57
Postharvest sorghum stems	44	9.2	408	74
Laboratory study				
Soybean leaves at full bloom	10	43.5	480	48
Stage 3 sorghum leaves	20	21.0	417	56
Soybean stems at full bloom	28	15.0	420	182
Postharvest sorghum leaves	38	10.8	412	43

approximates the amount of N mineralized in one cropping season. This assumption is based on the following ideas:

1. After an initial immobilization period, when net N mineralization has just begun, N mineralization can be described using first-order decay models, where the greatest amounts of N mineralized from a residue are released early in the mineralization process with less and less N released as time progresses (Frankenberger and Abdelmagid, 1985).
2. In the laboratory studies conducted at near-optimum temperature (25–35 °C) and moisture conditions (soil water contents near 60% water-filled porosity), between 70 and 80% of the total amount of N ever mineralized was mineralized within 11 wk after soil incorporation (Jensen, 1929; Fu et al., 1987; Frankenberger and Abdelmagid, 1985; Van Schreven, 1964). Our own unpublished results show that between 60 and 80% of the N mineralized in a 3-yr field study was mineralized in the first 110 d.
3. A comparison of mineralization studies done in the field vs. those conducted in the laboratory (where soil and residue types are similar) suggest that, under optimal laboratory conditions, mineralization can be up to 50% faster than in the field.

For laboratory and greenhouse incubations, the total accumulated-inorganic-N value reported at the end of the experiment in unamended soils was subtracted from the total accumulated N reported for residue-treated soils. Net immobilization was expressed as negative mineralization for simplicity. All authors reported residue N and C concentrations as total residue N and C, although methods for measuring N and C were not always given. For determining total N, Frankenberger and Abdelmagid (1985), Fu et al. (1987), Wagger et al. (1985), and two studies from the authors' work used modified methods for total Kjeldahl N, as described by Bremner (1982). Total C was determined using the method of Mebius (1960) or modifications of that method as reported by Nelson and Sommers (1982) for Fu et al. (1987) and Frankenberger and Abdelmagid (1985), respectively. Jensen (1929) used a combustion method for total C. Total residue C was determined using a Leco C analyzer (Leco Corp., St. Joseph, MI) in the experiments conducted by the authors.

In the studies conducted by the authors and by Wagger et al. (1985), lignin concentration was measured using Goering and Van Soest's (1970) permanganate digestion procedure; Frankenberger and Abdelmagid (1985) determined lignin concentration by boiling the samples with 4.9 mol L^{-1} HCl and 7.3 mol L^{-1} H_2SO_4 for 30 min, then washing, drying, weighing, and ashing. Millar et al. (1938) didn't report the method they used for lignin determination but, in general, the lignin values they reported are somewhat high compared with those reported elsewhere for similar residues.

Regression equations were fitted to each of the eight individual studies using the following regression models:

$$y = \beta_0 + \beta_1 (C/N) \quad [1]$$

$$y = \beta_0 + \beta_1 (N\ conc.) \quad [2]$$

$$y = \beta_0 + \beta_1 (N\ conc.)^{1/2} \quad [3]$$

where y is the N mineralized as a percent of the N applied in the crop residue, β_0 and β_1 are the fitted intercept and slope, and N concentration (g/kg) and C/N refer to the residue. Equations [1], [2], and [3] were also fitted to the pooled data from all studies.

Data in the various studies indicated that lignin concentration might influence the percent N mineralized from a given residue, even when the N concentration in the tissue was relatively high. Therefore, in those studies that reported lignin content (the studies by the authors: Frankenberger and Abdelmagid, 1985; Millar et al., 1937) the data were each fitted individually and as one data set to the following models:

$$y = \beta_0 + \beta_1 (N\ conc.) + \beta_2 (lignin) \quad [4]$$

Table 3. Coefficients and statistics of equations fit on the percent N mineralized vs. C/N ratios, N concentration, and the square root of N concentration.

Study†	Independent variable	Intercept β_0	Slope β_1	R^2	RMSE‡	n	F of regression
W.T. Frankenberger	C/N	76.07	−2.68	0.61	18.1	12	15.7**
	N conc.	−19.55	1.70	0.74	4.9	12	28.0***
	N conc.$^{1/2}$	−74.84	19.87	0.74	14.7	12	29.1***
M.H. Fu	C/N	50.98	−1.16	0.93	5.7	12	143.2***
	N conc.	−23.23	2.14	0.75	1.1	12	30.1***
	N conc.$^{1/2}$	58.28	17.87	0.82	9.4	12	45.9***
H.L. Jensen	C/N	54.11	−1.49	0.99	4.5	7	437.4***
	N conc.	−50.88	2.61	0.70	23.4	7	11.7*
	N conc.$^{1/2}$	−110.23	25.79	0.84	17.1	7	26.1**
H.C. Millar	C/N	47.99	−1.02	0.83	9.8	12	48.1***
	N conc.	−12.70	1.65	0.42	18.0	12	7.4*
	N conc.$^{1/2}$	−42.91	14.73	0.52	16.4	12	11.0**
D.A. Van Schreven	C/N	83.26	−2.43	0.91	14.1	4	19.2*
	N conc.	−63.13	4.60	0.97	8.5	4	57.2*
	N conc.$^{1/2}$	−134.67	37.10	0.95	9.9	4	41.1*
M.F. Vigil (field study)	C/N	40.82	−0.85	0.73	4.8	10	21.9***
	N conc.	−10.03	1.71	0.72	4.9	10	20.7**
	N conc.$^{1/2}$	−35.24	13.24	0.74	4.7	10	23.3**
M.F. Vigil (lab study)	C/N	74.86	−1.97	0.83	9.9	26	115.8***
	N conc.	−9.87	1.63	0.91	7.3	26	230.6***
	N conc.$^{1/2}$	−49.06	16.62	0.91	7.1	26	244.3***
M.G. Wagger	C/N	51.81	−1.01	0.50	8.2	4	2.6
	N conc.	8.32	2.14	0.43	8.9	4	4.9
	N conc.$^{1/2}$	−37.32	15.83	0.44	8.7	4	4.2
All data	C/N	58.89	−1.41	0.75	12.3	87	261.4**
	N conc.	−14.36	1.70	0.68	13.9	87	184.1***
	N conc.$^{1/2}$	−53.44	16.98	0.72	12.9	87	228.4***

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† Each study is referenced by the first author.
‡ RMSE = root mean square error.

$$y = \beta_0 + \beta_1 (\text{C/N}) + \beta_2 (\text{lignin}) \quad [5]$$

$$y = \beta_0 + \beta_1 (\text{N conc.})^{1/2} + \beta_2 (\text{lignin}) \quad [6]$$

where β_0, β_1, and β_2 are fitted regression coefficients and lignin concentration (g/kg) refers to the residue. Finally, using a subset selection procedure RSQUARE (SAS Institute, 1985), the chemical properties C, N, C/N, and lignin and several mathematical transformations of these properties (including the lignin/N ratio, the C/lignin ratio, the C/N ratio, and N concentration raised to the 0.5, 0.75, 1.5, and 2 powers) were tried in an attempt to find a good general relationship between the amount of net N mineralized and some chemical property of the residue. The models selected came from simultaneously fitting the percent N mineralized on residue N and residue C/N ratio to the various powers listed above. The models reported were the best fits as measured by R^2 and root mean square error (RMSE). In most cases, the other transformations didn't fit nearly as well as the square root and untransformed data, so we didn't include these here. Several other nonlinear regression models, which were more complicated, were also fitted. The nonlinear models weren't able to describe the data any better than the square-root transformation or the 0.75 transformation. For the sake of time and space, we have omitted the nonlinear models. For simplicity, models containing more than two independent variables were not reported. Regressions were fit on the data that reported residue lignin concentration separately from the rest of the data (n = 60) and on all the data (n = 87). The significance of the second independent variable as a predictor after adjusting for the first independent variable was tested using the method described by Weisberg (1980).

RESULTS AND DISCUSSION

The C/N ratios of each residue vs. the N concentration in those residues, are shown in Fig. 1. The closeness of the relationship suggests that residue C content must be nearly the same in all residues and, therefore, the C/N ratio and N concentration are really measurements of the same thing. A regression between

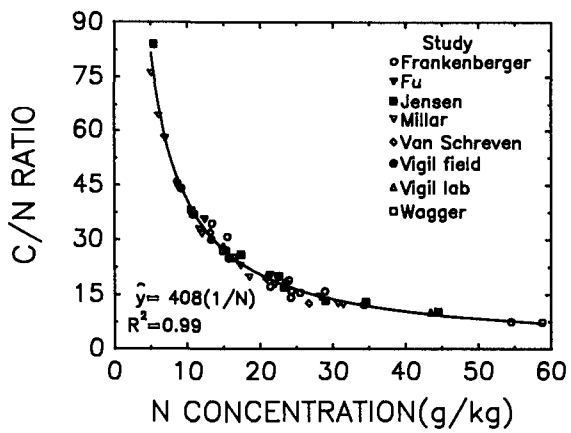

Fig. 1. The C/N ratios vs. the N concentration of the various crop residues used in this collection of studies. The solid line is the relationship as predicted by the equation given in the graph.

1/N concentration and C/N ratio produced the fitted equation given in Fig. 1, which had an R^2 of 0.99 and a RMSE of 2.08. The fitted average C concentration of 408 g/kg, from the equation in Fig. 1, is near the calculated average of 415 g/kg. Both values are near the average C concentration of 400 g/kg reported by Alexander (1977). Since N concentration is more easily measured than C/N ratio (only one analysis instead of two), we compared the two as predictors by fitting regression equations on the total N mineralized as a function of the C/N ratio and N concentration. Regression coefficients and associated statistics are given in Table 3. All of the fitted equations were significant, except those fitted to the Wagger et al. (1985) data. The lack of a significant fit with the Wagger et al. (1985) data set is more than likely due to the small size of the data set (n = 4), where a single data case greatly affected the results. If we used the numerical

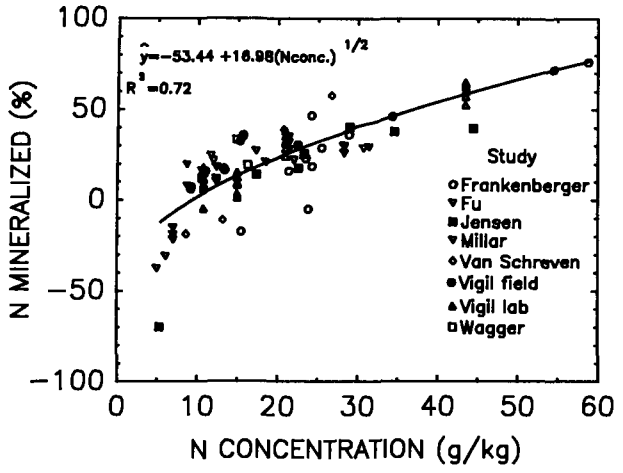

Fig. 2. Amount of N mineralized vs. N concentration. The solid line is predicted by the equation given in the graph. Symbols are measured data.

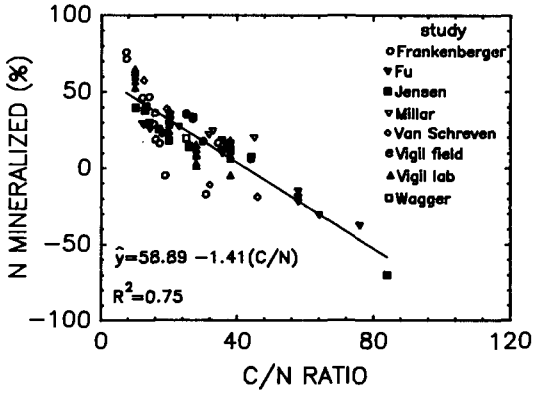

Fig. 3. Amount of N mineralized vs. C/N ratio. The solid line is predicted by the equation given in the graph. Symbols are measured data.

size of the F of regression as a criterion for comparing models, then the C/N ratio was the best predictor for three of the studies: Fu et al. (1987), Jensen (1929), and Millar et al. (1937). Nitrogen concentration or its square-root transformation were the best predictor for the other five studies: Frankenberger and Abdelmagid (1985), Van Schreven (1964), Wagger et al. (1985), the field study conducted by the authors (1989), and the laboratory study conducted by the authors. For six of the eight studies, the square-root transformation of N concentration was an improvement over N concentration, which reflects the slightly curved scatter observed in Fig. 2. When all of the data were included in a single fit, the best single predictor was the C/N ratio, with an R^2 of 0.75, (RMSE) of 12.3, and F of regression of 261.4. The regression equation of the percent N mineralized as a function of the C/N ratio fit to the combination of data from all of the studies is shown in Fig. 3. The fit on C/N ratio was only slightly greater than the fit on the square-root transformation of N concentration with an R^2 of 0.72, RMSE of 12.9, and F of regression of 228.4 (Fig. 2). The two equations fit to the combination of the experimental data drawn as lines in Fig. 2 and 3 were able to describe the main body of the data but weren't able to accurately predict the amounts of N mineralized at low N concentrations (Fig. 2) or very narrow C/N ratios (Fig. 3).

In general, for studies in which residue lignin content was reported, the addition of lignin content as a second independent variable increased the R^2 value and decreased the RMSE (Table 4). The inclusion of lignin content as a second independent variable was a significant predictor (after adjusting for the other variable, Weisberg [1980]) and contributed to the improvement of the fitted regression for the two studies conducted by the authors (Table 4). When all of the data in which residue lignin was reported was combined in one data set, the inclusion of lignin content as a second independent variable was a significant predictor and contributed to the improvement of the fitted regression (Table 4). The best overall fit on that data was with the square-root transformation of N concentration (Table 4). In that equation, the coefficient for percent lignin content was negative, indicating that increased residue lignin decreased the amount of N mineralized. That result agrees with what is known about lignin's resistance to microbial decomposition (Paul and Clark, 1989; Alexander, 1977). It

Table 4. Coefficients and statistics of regression equations fit to the percent N mineralized vs. C/N ratio, N concentration, the square root of N concentration, and lignin content.

Study†	First independent variable	Intercept β_0	Slope β_1	Lignin β_2	R^2	RMSE‡	n	F of regression
W.T. Frankenberger	C/N	75.78	−3.11	0.06	0.63	18.7	12	7.6*
	N conc.	−43.28	2.09	0.09	0.78	14.4	12	15.9**
	N conc.$^{1/2}$	−123.27	26.06	0.12	0.81	13.3	12	19.3***
H.C. Millar	C/N	89.12	−1.03	−0.27	0.87	8.9	12	31.2***
	N conc.	51.18	1.82	−0.44	0.54	17.0	12	5.3*
	N conc.$^{1/2}$	16.07	15.81	−0.42	0.63	15.2	12	7.7*
M.F. Vigil (field study)	C/N	54.51	−0.46	−0.42	0.82	4.1	10	16.5**
	N conc.	28.07	0.88	−0.42	0.80	4.4	10	14.4*
	N conc.$^{1/2}$	11.56	7.30	−0.40	0.81	4.3	10	15.4**
M.F. Vigil (lab study)	C/N	81.08	−1.82	−0.12	0.92	6.9	26	130.9***
	N conc.	−1.51	1.52	−0.07	0.93	6.3	26	159.9***
	N conc.$^{1/2}$	−37.28	15.44	−0.08	0.94	5.7	26	195.7***
All data§	C/N	65.65	−1.32	−0.08	0.73	12.4	60	75.5***
	N conc.	−5.01	1.52	−0.04	0.78	11.2	60	98.7**
	N conc.$^{1/2}$	−39.45	15.19	−0.05	0.79	10.8	60	108.3***

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
† Each study is referenced by the first author.
‡ RMSE = root mean square error.
§ All data in which residue lignin content was reported.

is surprising that the inclusion of lignin content didn't contribute significantly to the fitted equations of the other two data sets, especially because lignin is known to inhibit microbial degradation of plant tissues (Alexander, 1977).

Using the subset selection procedure RSQUARE (SAS Institute, 1985), the best two-parameter model for data reporting lignin content that included various transformations of N, C, C/N, and lignin was:

$$y = 0.62 + 1.338\ (\text{N conc.}) - 0.875\ (\text{lignin/N}) \quad [7]$$

The R^2, RMSE, F of regression of the fitted model, and the number of cases in the fitted regression were 0.80, 10.6, 115.2, and 60, respectively. The F of regression was significant at the 0.001 probability level. Both N concentrations and lignin/N were significant predictors in the fitted equation and the lignin/N ratio was a better predictor than lignin alone. The negative coefficient for the lignin/N ratio suggests that an increase in a residue's lignin content will decrease the amount of N released from that residue.

The best two-parameter model fit to all of the data from the experiments was:

$$y = -99.56 + 48.15(\text{N conc.})^{1/2} - 9.59(\text{N conc.})^{3/4} \quad [8]$$

The R^2, RMSE, F of regression, and number of cases in the fitted regression were 0.74, 12.6, 121.9, and 87, respectively. Both transformations were significant predictors in Eq. [8], and Eq. [8] was able to predict the amounts of N mineralized at lower N concentrations, which was not possible when only the square-root transformation was used. The critical residue N concentration at which neither net mineralization nor immobilization occurs can be determined from Eq. [8] by setting y equal to zero and solving numerically for N concentration. Likewise, the equation given in Fig. 3 for net mineralization as a function of C/N ratio can also be solved for a critical N concentration by setting y in the equation equal to zero, assuming residue C is 408 g/kg. When these calculations are applied to Eq. [8] and the C/N-ratio equation in Fig. 3, the critical N concentrations are 10.34 and 9.64 g N/kg residue, respectively. These values of 10.34 and 9.64 g N/kg residue correspond to C/N ratios of about 40. This critical C/N may be higher than values often reported, because in our study only net mineralization after extended incubation was considered. The approach we have taken is not useful for estimating short-term mineralization or mineralization kinetics.

The strength of the empirical approach used in this study is that it allows for a quick and simple way of arriving at a quantitative estimate of the amount of N that will mineralize from soil-incorporated crop residues based on the residue's N concentration, C/N ratio, and lignin concentration. Since the fitted equations are based on mineralization data collected at near-optimal soil moisture and temperature and because of the apparent first-order nature of N mineralization, the amounts of N mineralized estimated using these equations would be near the maximum expected in one cropping season. The fraction of this maximum potential actually realized in the field would depend on moisture, temperature, residue management, and perhaps other factors.

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