Accounting for seasonal nitrogen mineralization: An overview

M.F. Vigil, B. Eghball, M.L. Cabrera, B.R. Jakubowski, and J.G. Davis

ABSTRACT: Accurately predicting the amount of nitrogen (N) made available for crop use by N mineralization (N_{min}) of native soil organic matter (SOM) is complicated by different soils, climate, and management, all highly variable from one location to the next. In this paper, we have compiled seasonal estimates of N_{min} from eleven field studies. We only include data for native SOM and do not include organically-amended soils. Initially, the data sets were graphed and regression was performed on the data as is. To further analyze the data, and because different incubation times were used for the different studies, we normalized reported N_{min} to a twenty-week incubation period. Values of N_{min} for a season range between 0.4 and 152 kg N ha^{-1} (0.3 and 136 lb N ac^{-1}). The average amount of N_{min} for all of these studies was 49.3 kg N ha^{-1} (44 lb N ac^{-1}). A graph of N_{min} for all of the data against SOM shows a negative relationship. A simple linear fit on that data results in a non significant R^2 of 0.0008. A similar fit of all of the data against total N was also of little value. Eliminating the data collected from short incubations (less than fifteen weeks long) improved the fit; 42% of the variability in normalized twenty-week N_{min} could be explained by total N. Regression analyses of the total soil N and of SOM content on the seasonal N_{min} indicated that neither SOM nor total N is a good predictor for the seasonal N_{min} amount. Soil type, management, and climate at the various locations obviously influence the magnitude of the estimates. More importantly, this review supports the push for an accurate predictive simulation model for seasonal N_{min} that is non site-specific.

Keywords: Nitrogen mineralization, soil organic matter

Methods to predict the amount of inorganic N made available for crop use via N mineralization (N_{min}) of native soil organic matter (SOM) are needed to accurately assess crop fertilizer requirements. But the interaction between soil type, climate, and management, all highly variable from one location to the next, makes accurate prediction difficult.

Climate effects on N_{min} generally involve differences in temperature and moisture regimes. Campbell et al. (1984) reported that the effect of temperature on the N_{min} rate changed with latitude. Northern soils were affected more by incubation temperature than southern soils. Campbell et al. (1984) speculated that the decomposition rate, as a function of temperature, was related to the amount of readily decomposable organic matter in the soil. Not all organic materials decompose at the same rate. For example, water-soluble carbohydrates, amino acids, and amino-sugars have a short residence time in a soil. With an active microbial population under typical summer field conditions, they are usually consumed in a week or two. Organic matter that has been humified or derived from more resistant materials (lignin-associated) has a longer residence time under the same field conditions and may last years. In northern climates, where summers are

Merle F. Vigil is a soil scientist at the U.S. Department of Agriculture-Agricultural Research Service, Central Great Plains Research Station in Akron, Colorado; **Bahman Eghball** is a soil scientist in the Department of Agronomy at the University of Nebraska-Lincoln in Lincoln, Nebraska; **Miguel L. Cabrera** is a professor of soil science in the Department of Crop and Soil Sciences at the University of Georgia-Athens in Athens, Georgia; and **Brad R. Jakubowski** is a graduate research assistant and **Jessica G. Davis** is a soil scientist in the Department of Soil and Crop Sciences at Colorado State University in Fort Collins, Colorado.

Reprinted from the *Journal of Soil and Water Conservation*
Volume 57, Number 6

cooler and shorter, less decomposition of organic litter and native soil organic matter will happen in a given year, resulting in a buildup of more easily decomposed material over time. In southern climates, the summer is longer, allowing for more complete decomposition of most of the litter material. Over a long period in southern soils, only the most resistant organic materials are left behind, whereas in northern soils, both easily decomposable and resistant materials can accumulate. When northern and southern soils are brought into the laboratory and incubated at different temperatures, a smaller increase in the rate of N_{min} at warmer incubation temperatures is found in the southern soils than is measured in northern soils. Vigil and Kissel (1995) reported that temperature's effect on the rate of N_{min} in four Kansas soils could be described by the following nonlinear equation:

$$TF = 0.011[e^{0.13(ST)}] \quad (1)$$

where TF is the change in the first order reaction rate of N_{min} as a function of soil temperature in °C, and ST is the incubation soil temperature. An evaluation of that equation indicates that plant residue decomposition at 25°C (77° F) is 3.7 times faster than at 15°C (59° F) and 13 times faster than at 5°C (41° F). The effect of temperature in changing the rate of N_{min} over a given period is important in determining the total amount of N_{min}.

In a similar manner, soil water content will affect the N_{min} rate. Linn and Doran (1984) reported that for many soils microbial activity was maximized at soil water filled pore space (WFPS) values near 60%. At WFPS values greater than 60%, anaerobic conditions predominate, slowing the rate of decomposition. In unpublished laboratory experiments, we found that decomposition was fastest between 50 and 55% WFPS, with very little decline in the rate of decomposition until water filled porosities dropped below 50%. Cabrera and Kissel (1988) used a relationship between optimum soil water content for N_{min} and actual soil water content developed by Myers et al. (1982) to adjust first order rate constants for N_{min}. The Cabrera and Kissel experiment (1988) is of particular interest because it was designed to specifically evaluate methods for predicting N_{min} under field conditions. The method involved measuring the net N_{min} from soil samples in laboratory incubations and then fitting the results to first-order models of N_{min}:

$$N_{min} = N_o (1-e^{kt}) \quad (2)$$

where N_o is the numerical value of "the size" of the potentially mineralizable N pool, k is the first order rate constant for N_{min}, and t is time in days. The model's rate constant (k) is then adjusted by a soil water and a soil temperature factor. They found errors as large as 114%, with over-prediction being the biggest problem with the method. They speculated that the soil water content factor of Myers et al. (1982) was better than what was used in previous studies, but was probably still a source of some of the over-prediction error. They also speculated that the use of disturbed soil samples for estimating equation parameters was a cause of over-prediction. The water content relationship used was:

$$W = (WC-AD/OWC-AD) \quad (3)$$

where WC is the water content in the field, AD is the air dry soil water content (calculated as 50% of the water content at -1.5 MPa (-15 bars)), and OWC is the optimum water content (near -0.02 MPa (-.2 bars)). Using this relationship to adjust the rate constant decreased the difference between measured and predicted N_{min} by about 20%.

Management and soil texture also influence the N_{min} rate in a soil. Tillage mixes the soil and organic matter with each pass, breaking up soil aggregates and exposing more organic matter to microbial attack. Well-aggregated soil, where soil clay-sized particles are bound about organic materials, physically protects soil organic matter, increasing the residence time of the material in soil (Beare et al. 1994; Jastrow 1996). Paustian et al. (2000) summarized the data of Angers et al. (1993), Camberdella and Elliot (1993), Beare et al. (1994), and Franzleubbers and Arshad (1996) and found a decrease in aggregate stability with tillage frequency. Six et al. (1999) developed a conceptual model of soil aggregate turnover and decomposition with tillage. In that model, clay particles are thought to become encrusted about organic litter, leading to increased physical protection. Craswell and Waring (1972) demonstrated that grinding a soil sample increased N_{min} more in soils with high clay content than with soils with less clay.

Simple "rules of thumb" for estimating potentially mineralizable N for a season, based on soil organic matter content, total soil N (TN), or total soil C (TC) have been used as rough predictors for making fertilizer recommendations. One "rule of thumb", used in the Central Great Plains region, assumes 30 lb of available N will mineralize per ac (34 kg N ha^{-1}) for every 1% SOM in a soil (Soltanpour 1979; Waskom 1994). With the above understanding in mind, we compiled seasonal estimates of N_{min} from several field studies that varied in soil type, location, and climate. For a first approximation, we included only data sets for native SOM and did not include organically amended soils. Our objectives were: (1) to look for simple rules of thumb regarding chemical composition of the soils that might act as predictors of the total amount of N_{min} from a soil in a season, and (2) to compile field N_{min} documented in the literature from various field studies.

Methods and Materials

The amount of N_{min} made available in one season under field conditions was gathered from the literature from several field studies (Table 1). Only one lab study was included (Coyne et al. 1998). Studies that were included used one of several methods to estimate N_{min}. Method 1 used the *in situ* resin core. Method 2 was an N balance with regression modeling. In Method 2, soil samples for inorganic N prior to cropping and after cropping were taken and regression modeling on plant uptake N as a function of SOM and inorganic N was used to estimate N release per % SOM. Method 3 was a simple N balance method: here the estimate of N_{min} was calculated using the following relationship:

$$N_{min} = \text{inorganic N (end)} - \text{inorganic N (start)} + \text{plant N uptake} - \text{N gains} \quad (3)$$

where soil sampling for inorganic N happened prior to cropping (start) in cropped plots or just at the beginning of the season in non-cropped plots and at the season's end (end), with crop N uptake added to the potential difference in inorganic N accumulated in the soil. In some cases, N gains were measured if fertilizer or rainfall N was added or measured (Cabrera and Kissel 1988). In method 4, the N accumulated in moist soil, placed in polyethylene bags, tightly sealed, and buried (buried-bag technique; Adams et al. 1989) was used to estimate seasonal N_{min}. Finally, in method 5, ^{15}N pool dilution (Coyne et al. 1998; Davidson et al. 1991) was

Table 1. Nitrogen mineralized (N_{min}) in a season from the soils of several different locations and experiments. Soil organic matter (SOM) and total nitrogen are also included if reported.

Author[†]	Soil	Method	SOM %	Total soil N %	Time (weeks)	Management	Nmin Kg/ha[‡]	Nmin /% SOM Kg/ha[§]
Eghball 2000 Central Nebraska	Sharpsburg silty clay loam	*In situ* resin core method	3.21 ¥	0.16	19	irrigated corn	46 (48)	14 (15)
					16		58 (73)	16 (23)
					18		69 (71)	19 (22)
Geist 1970 Eastern Colorado	Weld loam	regression modeling	1.50	—	12	irrigated barley	74 (74)	55 (49)
ARS/Akron 2000 Akron, Colorado	Weld silt loam	*In situ* resin core method	1.47	0.097	45	irrigated corn	67 (30)	45 (20)
Cabrera 1988 Eastern and Western Kansas	Kahola silt loam 1983	simple N balance	2.56 ¥	0.126	15	sorghum	32 (43)	12 (17)
	Kahola silt loam 1984				23		51 (44)	20 (17)
	Haynie very fine sandy loam 1983		0.86	0.077	17	sorghum	43 (51)	50 (59)
	Haynie very fine sandy loam 1984				21		45 (43)	52 (50)
	Richfield silt loam 1983		1.68	0.119	15	sorghum	31 (41)	18 (24)
	Richfield silt loam 1984				18		36 (40)	21 (24)
	Wymore silty clay loam 1983		—	0.145	5	fallow	21 (84)	—
	Wymore silty clay loam 1984				12		75 (125)	—
	Haynie very fine sandy loam 1983		0.86	0.077	4	fallow	23 (115)	27 (134)
	Haynie very fine sandy loam 1984				15		107 (143)	124 (166)
Schmidt 1999 Northern Sweden	Heath	buried bag technique	79.7	0.019	52	dwarf shrub communities	.73 (0.28)	0 (0)
	Fellfield organic soil		56.4	0.019			.42 (0.16)	0 (0)
Erikson 1999 Maryland	sand	simple N balance	1.49	0.08	69	rye/corn unamended check plots	152 (44)	102 (30)
							120 (36)	81 (23)
Kolberg 1999 Eastern Colorado	Weld silt loam	*In situ* resin core method	1.70	0.1	24	wheat/fallow	44 (37)	25 (22)
			1.70	0.1		wheat/corn/fallow	25 (23)	16 (14)
	Keith clay loam		1.50	0.1		wheat/fallow	51 (48)	37 (31)
			1.50	0.1		wheat/corn/fallow	27 (25)	20 (17)
Gavi 1997 Stillwater, Oklahoma	Norge loam	simple N balance	2.05	0.11	22	unamended check plots	42 (38)	21 (19)
Mueller 1998 Frederiksberg, Denmark	sandy loam	simple N balance	2.23 ¥	0.14	51	unamended check plots	35 (14)	16 (6)
De Neve 1998 Gent, Belgium	loamy sand	simple N balance	1.96	0.097	18	unamended check plots	43 (54)	22 (28)
Coyne 1998 Mulenberg County, Kentucky	silt loam	15-N pool dilution	0.69 ¥	0.021	29	unamended check plots	14 (10)	20 (15)
Soltanpour 1979 Colorado	any soil in Colorado	regression	—	—	crop season	any crop	—	30

[†] Studies referenced by the last name of the first author of each study.

[‡] The amount of nitrogen mineralized (N_{min}) in a season. The value in parentheses is the amount of N_{min} that would come available in a twenty week period.

[§] This column is the amount of N_{min} in a season for each percent of soil organic matter (SOM) in the soil. The value in parentheses is the amount of N_{min} for each percent SOM in a twenty week period.

[¥] All SOM values in the Cabrera (1988), Mueller (1988), Eghball (2000), and Coyne (1998) studies were converted from total C to SOM by multiplying total C by 1.72.

used for estimating N_{min}. We included data sets that reported field incubation periods that were at least four weeks long and that had measurements of the total N or total C and/or SOM. If only total C was reported, we converted the reported value to organic matter by multiplying soil C% by 1.72 (assuming that soil organic matter was 58% C, Nelson and Sommers 1982).

All data was corrected to N_{min} in twenty weeks by dividing the N_{min} amount by the number of weeks incubated and then multiplying by 20.

$$N_{min} \text{ (20 wk)} = N_{min} / \text{wk} \times 20 \qquad (4)$$

In the case of Coyne et al. (1998), the estimate of N_{min} per day was multiplied by 140 d (20 wk) to make comparison with the other data sets reasonable.

One data set has not been published (Akron data). In that study, *in situ* measurements of N_{min} were made in an irrigated corn (*Zea Mays* L.) field at the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) Central Great Plains Research Station in Akron, Colorado on a Weld and a Rago silt loam (fine, smectic, mesid, Aridic Paleustolls) in 1999 and 2000. The "*in situ* resin core method" is described in detail by Kolberg et al. (1999) and Eghball (2000). The *in situ* resin core method involves driving aluminum conduit tubes 5 cm (2 in) in diameter and 15 cm (6 in) long into the soil. The tube containing a semi-undisturbed core is then extracted from the soil, and 1.5 - 2 cm (0.6 - 0.8 in) of soil is removed from the bottom of the tube to make room for the resin bag. The resin bag (made of nylon) containing 20 ml (0.71 oz) of Na^+ and Cl^- exchange resin are snugly installed in the bottom of each tube to capture ions that might leach or diffuse from the soil core. The tube with the resin bag is replaced in the field and then removed after a set time. Accumulated N_{min} in the soil and in the resin bag is extracted with 2N KCl and inorganic N is measured using a LACHAT auto-analyzer.

N_{min} data was graphed against SOM and TN and simple linear regression equations were fitted to data that visually appeared to have a relationship. Case analyses were performed in an attempt to improve potential relationships by removing data collected from short incubations (data collected from soil incubated for less than fifteen weeks).

Results and Discussion

In general, the data sets included here provide a wide range of field N_{min}. Values of N_{min} for a season range between 0.4 and 152 kg N ha^{-1} (0.3 and 136 lb N ac^{-1}) (Table 1). The Schmidt et al. (1999) data is of particular interest. In their study, the authors worked with arctic soils where the average summer air temperature was only 2 - 3°C. The SOM amount at that location was the highest of all locations included in this compilation of data, yet their measurement of seasonal N_{min} was less than 1 kg ha^{-1} yr^{-1} (less than 2 lb of N ac^{-1} yr^{-1}). An interpretation of that data set emphasizes the importance of soil temperature's effect on seasonal N_{min} amounts. The Kolberg et al. (1999) data is also of particular interest because different amounts of N_{min} were measured on the same soil type under different management. In that experiment, measurements of field N_{min} were made during the fallow phase of two rotations: winter wheat/summer fallow (WF) and winter wheat/corn/summer fallow (WCF). Measurements were made at two locations: Stratton and Sterling Colorado on a Keith silt loam and a Weld silt loam. Regardless of soil type and location, the soil in WF plots mineralized almost twice as much N as the WCF plots. The authors indicated that crop-residue amounts were greater with WCF and speculated that greater N immobilization may have caused less net N_{min} in the WCF rotation as compared to WF. Whereas the authors reported that precipitation differences between locations appeared to influence the N_{min} rate, management had a greater effect than either soil or location. The Kolberg et al. (1999) study provides evidence for how important crop residues are in influencing seasonal N_{min} amounts.

Figure 1
Nitrogen mineralized in a season (kg ha^{-1}) as a function of soil organic matter (%). The dashed line is the simple linear regression line fitted to the data.

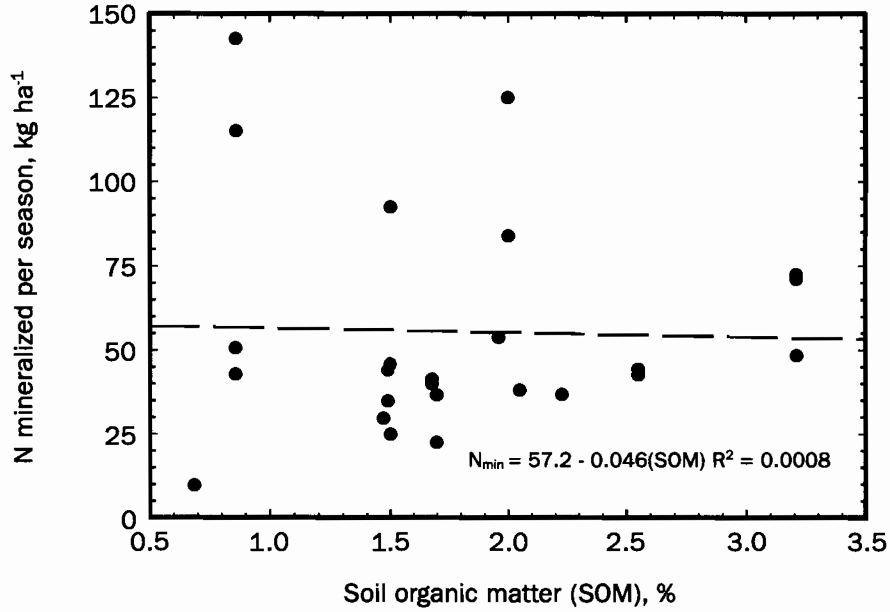
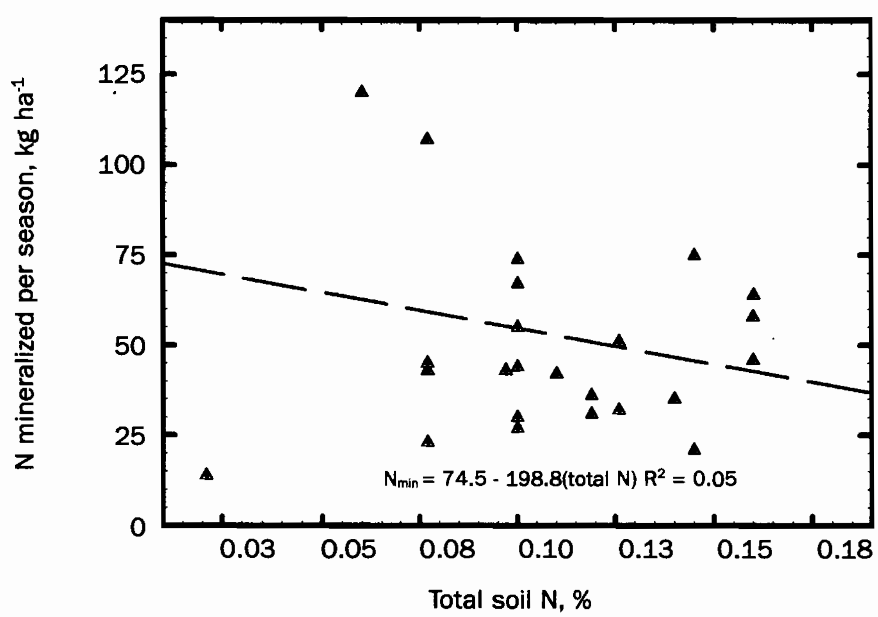


Figure 2
Nitrogen mineralized (kg ha^{-1}) in a season as a function of total soil N (%). The dashed line is the fitted regression equation.



Soltanpour (1979) published the rule of thumb: 34 kg N ha^{-1} (30 lb N ac^{-1}) will mineralize in one cropping season for every 1% of SOM. The average amount of Nmin per 1% SOM for all of these studies is 33 kg N ha^{-1} (29 lb N ac^{-1}) (Table 1), which indicates that Soltanpour's value is a "reasonable" rule of thumb. If the Schmidt et al. (1999) data is excluded, the average N_{min} is 36 kg N ha^{-1} per

Figure 3

Nitrogen mineralized in twenty weeks as a function of total soil N. All data is included except I.K. Schmidt et al. (1999). The dashed line is the fitted regression equation.

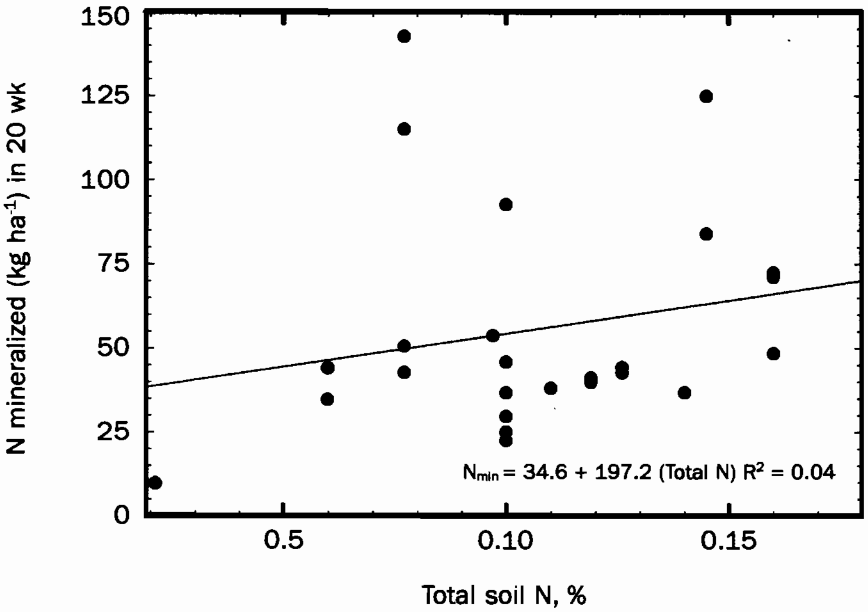
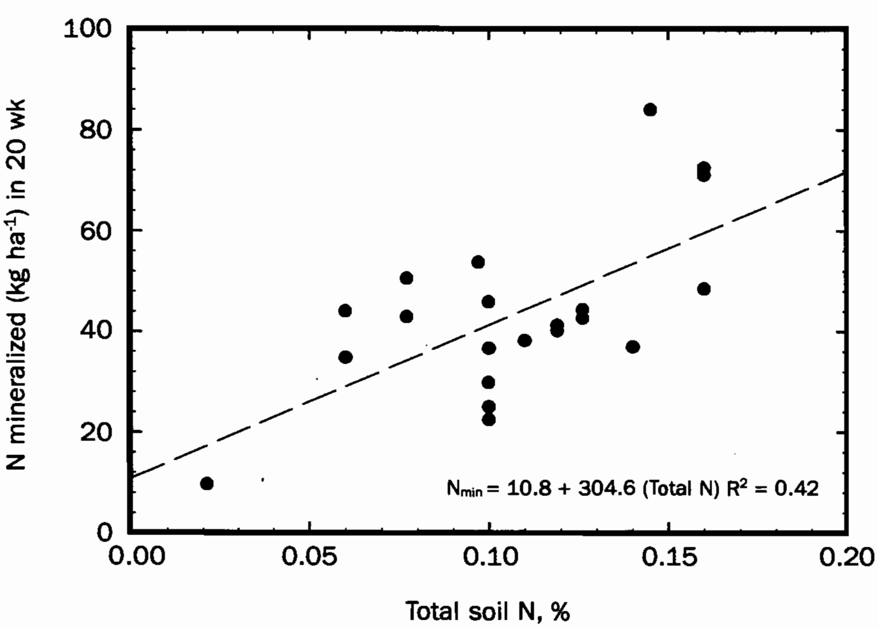


Figure 4

Nitrogen mineralized (kg ha⁻¹) in twenty weeks as a function of total soil N (%); where data from short incubations less than 15 weeks are eliminated from the regression. The dashed line is the fitted regression equation.



1% SOM (32 lb N ac^{-1}). But a graph of N mineralized for all of the data against SOM gives a negative relationship with a non significant R^2 of 0.0008 (Figure 1). A similar fit of all of the data against total N is also of little value (R^2 of 0.05, Figure 2). Regression analysis of the total soil N and of SOM content on the seasonal N_{min} amount indicates that neither SOM or total N is a good predictor for the seasonal N_{min} amount. Because the data from the various experiments all had different incubation times, we normalized all of the data to a common twenty week period. Based on a twenty week incubation period, N_{min} values in Table 1 range between 10 and 142 kg of N ha^{-1} (9 and 127 lb N ac^{-1}) (Figure 3). After normalizing all data to a twenty week incubation period, and if all of the data collected from short incubations (less than fifteen weeks) are eliminated from the data set 42% of the variability in the twenty week N_{min} amount can be explained by total N (Figure 4). That regression looks somewhat promising, but also indicates that 58% of the variability in the N_{min} amount is not explained by total soil N. Our approach to combine published N_{min} totals from the literature into one data set, even though different soils, locations, and methods were used with each study, ensured that some intrinsic errors specific to each study might cause difficulty in developing a usable, simple relationship.

Variability in climate (moisture and temperature), soils (texture, chemical, and physical properties) and management (tillage, irrigation management, and crop grown) affect how much seasonal N_{min} occurs. Considering that all of these factors are different for individual fields complicates accurate N_{min} prediction. The real need is for a "simple functional model" that can be easily manipulated and that takes into account climate, soils, and management, an old idea that has not yet been achieved. Many functional relationships between N_{min} rate, soil temperature, and soil water content have been developed, but still need testing and validation. Relationships between a soil's texture, N_{min} rate, and N immobilization also need more work before we can have confidence in their predictive accuracy.

Summary and Conclusions

A graph of N mineralized for all of the data against SOM gives a negative relationship with a non significant R^2 of 0.0008. A similar fit of all of the data against total N is also of little value. After normalizing all data to a twenty week incubation period, and eliminating data collected from short incubations (less than fifteen weeks), 42% of the variability in the twenty-week N_{min} amount can be explained by total N. Regression analyses of the total soil N and of SOM content on the seasonal N_{min} amount indicates that neither SOM or total N is a good predictor for the seasonal N_{min} amount. Soil type and management as well as climate at the various locations obviously influences the magnitude of the estimates. A "rule of thumb" that can be used is 33 to 36 kg of N ha^{-1} (29 to 32 lb of N ac^{-1}) will mineralize in a twent season for every 1% of SOM in the above "rule" is an average of data that from 0 to 166 kg N ha^{-1} per 1% of SOM (0 to 148 lb N ac^{-1}) and so, depending on the location, using this rule could mean an error of 500 to 3000%. This report demonstrates that current approaches to predicting seasonal N_{min} from soil chemical properties have generally been unsuccessful and a research effort to develop a non site-specific predictive model for seasonal N_{min} is needed.

Acknowledgement

The authors wish to thank USDA-ARS technician Donna Fritzler for her help with gathering the various manuscripts from the literature for this publication.

References Cited

Adams, M.A., P.J. Polglase, P.M. Attiwill, and C.J. Weston. 1989. In situ studies of nitrogen mineralization and uptake in forests soils: some comments on methodology. Soil Biology and Biochemistry 21:423-429.

Angers, D.A., N. Samson, and S. Legere. 1993. Early changes in water-stable aggregation induced by rotation and tillage in a soil under barley production. Canadian Journal of Soil Science 73:51-59.

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994. Water-stable aggregates and organic matter fractions in conventional and no-tillage soils. Soil Science Society of America Journal 58:777-786.

Cabrera, M.L. and D.E. Kissel. 1988. Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. Soil Science Society of America Journal 52:1027-1031.

Camberdella, C.A. and E.T. Elliot. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Science Society of America Journal 57:1071-1076.

Campbell, C.A., Y.W. Jame, and G.E. Winkleman. 1984. Mineralization rate constants and their use for estimating mineralization in some Canadian prairie soils. Canadian Journal of Soil Science 64:333-343.Coyne, M.S., Q. Zhai, C.T. Mackown, and R.I. Barnhisel. 1998. Nitrogen transformation rates in soil at a surface coal mine site reclaimed for prime farmland use. Soil Biology and Biochemistry 30(8/9):1099-1106.

Craswell, E.T. and S.A. Waring. 1972. Effect of grinding on the decomposition of soil organic matter. I. The mineralization of organic nitrogen in relation to soil type. Soil Biology and Biochemistry 4:427-433.

Davidson, E.A., S.C. Hart, C.A. Shanks, and M.K. Firestone. 1991. Measuring gross nitrogen mineralization, immobilization and nitrification by ^{15}N isotopic pool dilution in intact soil cores. Journal of Soil Science 42:35-349.

De Neve, S. and G. Hofman. 1998. N mineralization and nitrate leaching from vegetable crop residues under field conditions: a model evaluation. Soil Biology and Biochemistry 30:2067-2075.

Eghball, B. 2000. Nitrogen mineralization from field-applied beef cattle feedlot manure or compost. Soil Science Society of America Journal 64:2024-2030.

Erikson, G.N., F.J. Coale, and G.A. Bollero. 1999. Soil nitrogen dynamics and maize production in municipal solid waste amended soil. Agronomy Journal 91:1009-1016.

Franzleubbers, A.J. and M.A. Arshad. 1996. Water-stable aggregation and organic matter in four soils under conventional and zero tillage. Canadian Journal of Soil Science 76:387-393.

Gavi, F., W.R. Raun, N.T. Basta, and G.V. Johnson. 1997. Effect of sewage sludge and ammonium nitrate on wheat yield and soil profile inorganic nitrogen accumulation. Journal of Plant Nutrition 20:203-218.

Geist, J.M., J.O. Reuss, and D.D. Johnson. 1970. Prediction of nitrogen fertilizer requirement of field crops: II Application of theoretical models to malting barley. Agronomy Journal 62:385-389.

Jastrow, J.D. 1996. Soil aggregate formation and the accrual of particulate and mineral associated organic matter. Soil Biology and Biochemistry 28:656-676.

Kolberg, R.L., D.G. Westfall, and G.A. Peterson. 1999. Influence of cropping intensity and nitrogen fertilizer rates on in-situ nitrogen mineralization. Soil Science Society of America Journal 63:129-134.

Linn, D.M. and J.W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. Soil Science Society of America Journal 48:1267-1272.

Mueller, T., L.S. Jensen, N.N. Nielsen, and J. Magid. 1997. Turnover of carbon and nitrogen in a sandy loam soil following incorporation of chopped maize plants, barley straw and blue grass in the field. Soil Biology and Biochemistry 30: 561-571.

Myers, R.J.K., C.A. Campbell, and K.L. Weier. 1982. Quantitative relationship between net nitrogen mineralization and moisture content of soils. Canadian Journal of Soil Science 62:111-124.

Nelson, D.W. and L.E. Sommers. 1982. Total carbon, organic carbon and organic matter. Pp. 539-578. In: A.L. Page (ed). Methods of Soil Analysis: Part 2. Agronomy Monograph No. 9. Madison, WI: American Society of Agronomy, Inc.

Paustian, K., J. Six, E.T. Elliot, and H.W. Hunt. 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48:147-163.

Schmidt, I.K., S. Jonasson, and A. Michelsen. 1999. Mineralization and microbial immobilization of N and P in arctic soils in relation to season, temperature and nutrient amendment. Applied Soil Ecology 11:147-160.

Six, J., E.T. Elliot, and K. Paustian. 1999. Aggregate and SOM dynamics under conventional and no-tillage systems. Soil Science Society of America Journal 63:1350-1338.

Soltanpour, P.N. 1979. Guide to fertilizer recommendations in Colorado: soil analysis and computer process. Colorado State University Cooperative Extension Service, Fort Collins, Colorado.

Vigil, M.F. and D.E. Kissel. 1995. Rate of nitrogen mineralized from incorporated crop residues as influenced by temperature. Soil Science Society of America Journal 59:1636-1644.

Waskom R.M. 1994. Best management practices for nitrogen fertilization. Colorado State University, Cooperative Extension Bulletin XCM-172.