Predicting Soil Organic Matter Nitrogen Mineralization

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ABSTRACT

The objectives of this study were to develop a model for soil organic matter (SOM) nitrogen (N) mineralization that required minimal inputs, to test the model using independent data sets, and to determine if the results could be used in adjusting commercial N fertilizer recommendations. A sequential 1st order model where N Pool I mineralized before N pool II mineralized was first evaluated but was not used because N pool I was an experimental artifact due to a N mineralization flush that resulted from drying soil at 40˚C, then rewetting. The N Pool II portion of the sequential model which was not impacted by drying and rewetting replaced the sequential model. The rate constant for N Pool II, k_{II}, was a constant that was adjusted monthly for differences in soil temperature and moisture. A daily time step was used to allow N mineralization estimates from one date to another. Simulations began in the month where temperature exceeded 10°C. Model predictions were compared to those in published studies in Northern California and Illinois.

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In the first California study, model predictions were near observed values in four of five locations. In the second California study, model predictions were within the 95% confidence interval of those based on laboratory incubation corrected for field temperature and moisture regimes. In a third study, unfertilized corn yields were compared to seasonal N mineralization predictions plus N from the prior crop for fifteen Illinois soils. The result was 32.0 kg corn per kg seasonal available N as compared to the typical value of 67.5 kg corn per kg commercial N fertilizer. N mineralization predictions for Illinois soils were related to total N suggesting that an equation could replace simulation modeling for a given soil/location combination. It is proposed that the N mineralization model which has readily obtainable inputs (total N, bulk density, monthly weather) could be used in conjunction with field studies to refine commercial N fertilizer recommendations.

Abbreviations: FR, fertilizer response; NOAA, National Oceanic and Atmospheric Administration; WHC, water holding capacity; FS, fertilized soil; US, unfertilized soil; PMN, potentially mineralizable N; BD, bulk density

Core Ideas

Includes a detailed description of the 1st order model including soil temperature and moisture correction factors.

The 1st order model N mineralization predictions for Northern California and Illinois soils suggested the model would have application to a variety of soils.

A protocol is proposed that would compare unfertilized crop yields to N mineralization predictions to establish the contribution of N mineralization to yield and provide adjustment to commercial N fertilizer recommendations.

Morris et al. (2017) presented a detailed review of how nitrogen (N) mineralization from soil organic matter (SOM) is critical in making N fertilizer recommendations that are sound from agronomic, economic, and environmental standpoints. Toward that end a variety of mechanistic models have been proposed. In a review of modeling N mineralization, Benbi and Richter (2002) concluded that site-specific mechanistic model parameters were difficult to relate to soil properties which limited widespread application. They viewed this limitation as a "challenge" to overcome and suggested a common experimental method would be helpful. Morris et al. (2017) evaluated computer models for N mineralization and N soil tests. They identified two important weaknesses in computer models: inputs too detailed to be practical and lack of real-time weather data.

A model where two SOM N pools mineralized by 1st order kinetics in sequence was proposed by Gilmour and Mauromoustakos (2011). The percentage of total N and k_I for N Pool I were functions of 3-d CO_2-C evolution, total N, and clay content. The rate constant for N Pool II, k_{II}, was considered a constant as it was not correlated with total N, 3-d CO_2-C, and/or clay content. The Gilmour and Mauromoustakos (2011) model was based on a laboratory study conducted by Schomberg et al. (2009). In that study, soils were crushed and dried at 40˚C, stored, then rewetted prior to incubation at 35˚C. This pretreatment likely created a N flush making N Pool I an artifact and not useful to predict N mineralization for field conditions.

The cause of the N flush has been the subject of several studies. Cabrera and Kissel (1988) attributed the N flush to rewetting dried (40°C) and sieved (2 mm screen) soil. They also concluded that two, simultaneous 1st order models best described N mineralization including the flush, while a single 1st order equation was adequate when the flush was excluded. Cabrera (1993) compared N mineralization in dried and rewetted soils to soils that were only rewetted. N mineralization in the latter followed zero order kinetics, while N mineralization in the former followed simultaneous first and zero order kinetics. The N flush has been noted in other studies where soil was air-dried, sieved (2 mm), rewetted and incubated at 35°C (Marion et al., 1981; Griffin and Laine, 1983). At 20°C, Curtin et al. (2014) did not observe a N flush in field moist soils that were sieved (4 mm), but not dried. Mikha et al. (2005) attributed the initial N flush for field moist soil that had been sieved (6 mm) and rewetted to decomposition of microorganisms. When that soil was allowed to dry and then rewetted four times, an increase in N mineralization was observed each time the soil was rewetted, but the increase was not sufficient to overcome the decline in N mineralization due to drying. Borken and Werner (2008) concluded that the N flush that has been observed when dry soil is rewetted often results in an increase in N mineralization over a field moist soil. They suggested that the N flush was due to "microbial and plant necromass, lysis of live microbial cells, release of previously protected solutes and exposure of previously protected organic matter." Borken and Werner (2008) also concluded that wetting and drying cycles under field conditions usually resulted in smaller N mineralization than soils near optimum moisture. Overall, the N flush observed for soils that have been dried, sieved, and rewetted then incubated at 35°C is likely much larger than under field conditions where temperatures are usually lower and soil moisture fluctuates throughout the year.

Thompson et al. (2015) used the Maize-N model requiring soils data (SOM content, soil texture), weather data, and site management information as inputs and seasonal N mineralization as the output. The range of growing season N mineralization for Missouri, Nebraska, and North Dakota locations was 15 to 140 kg ha^{-1}. Graphical representation of predicted N mineralization appeared to be related to SOM for more than 80% of data points. Geisseler et al. (2019) used an organic N budget that included plant residues and roots, long-term loss of SOM N, and rhizo-deposition to estimate N mineralization where total N inputs were equated to N mineralization for soils in the Central Valley of California. N mineralization was from 76 to 123 kg ha^{-1} yr^{-1} using this approach. In the same study, N mineralization in undisturbed soil cores incubated at 25˚C and optimum soil moisture for ten weeks provided baseline N mineralization. These values were then corrected for field soil temperature and moisture to predict annual and growing season N mineralization. The annual N mineralization mean was 243 kg ha^{-1} yr^{-1} with 49% occurring during the growing season. Banger et al. (2019) used a modified version of the Century model and the gSSURGO model to estimate N mineralization. This model requires an extensive soil data set (texture, bulk density, albedo, drainage constants, and runoff curve number) and a detailed weather data set (daily solar radiation, daily maximum temperature, daily minimum temperature, precipitation, pan evaporation, and relative humidity). They concluded the model performance was “fair.” Yet, simulated soil N concentrations were correlated with observed values for four ranges of cumulative precipitation from January to July.

Research has increasingly focused on relating soil properties to N mineralization. Khan et al. (2001) proposed a simple N soil test that was correlated with the amino sugar N. This soil test, N-test, differentiated locations in Illinois where corn (*Zea mays* L.) would be responsive to commercial N fertilization from those that would not be responsive. Gilmour (2009) using the same data set and a 1st order model for N mineralization made a similar differentiation. Ros et al. (2011) reviewed over 200 publications on the subject and concluded that soil tests designed to measure N mineralization were no better than total N in estimating N mineralization in the laboratory or field.

Osterholz et al. (2017) measured gross N mineralization using a ^{15}N pool dilution technique and the potential mineralizable N (PMN) soil test (Keeney and Bremner, 1966). SOM from six soils from the Midwest and Israel were evaluated for 32 properties. Regression equations were developed that could predict about 80% of the variability in gross N mineralization and PMN. A literature review by Clark et al. (2019) showed that PMN can be used to assist N management in several crops. To better understand what was contributing to PMN, they determined partial R^2 values for 20 soil properties and weather parameters. The value of PMN preplant could be estimated from %sand, total N, pH-water, NO_3-N, and the Shannon Diversity Index (SDI) modified for use in determining precipitation variability by Bronikowski and Webb (1996). The latter Index included pi (the ratio of daily precipitation to the sum of daily precipitation and the number of days (n) for a given period. The overall R^2 was 0.54 with total N contributing 0.33 to that value which supported Ros et al. (2011) conclusion regarding total N. Miller et al. (2019) found four equations were needed to predict N mineralization in 57 soils in California. Only one of those equations had total N as an independent variable. Total C was an independent variable in three of the four equations.

The objectives of this study were to develop a model for N mineralization that required minimal inputs, to test the model using independent data sets, and to determine if the results could be used in adjusting commercial N fertilizer recommendations.

MATERIALS AND METHODS

The sequential model of Gilmour and Mauromoustakos (2011) was used in initial modeling. Where intact cores were used (Geisseler et al., 2019; Miller et al. 2019), the rate constant for N Pool I (k_I) equaled that of N Pool II (k_{II}) in seven of eight cases. Thus, the sequential model was replaced with N Pool II alone where N mineralization could be predicted using Eq. 1 below,

$$\%N_{min} = \%N_{t1} \{1 - \exp(-k_{II}(t_2 - t_1)\} \quad [1]$$

Percent N_{min} is the percentage of total N mineralized between time 1 (t_1) and time 2 (t_2) and k_{II} is the 1st order rate constant. The mean value of k_{II} from Gilmour and Mauromoustakos (2011) was 0.0019 wk^{-1} at 35˚C and optimum moisture. The latter was converted to d^{-1} at 25˚C and optimum moisture by dividing by 7 then 1.29 (Q_{10}) to give k_{II} equal to 0.00021 d^{-1}. This Q_{10} was the ratio of temperature/moisture (TM) factors at 35˚C to 25˚C and 55% water holding capacity (WHC) from Eq. 2 below. The value of k_{II} was essentially the same as the first order rate constant used by Gilmour (1998) for decomposition of SOM (0.00020 d^{-1}). Total N (g kg^{-1}) was converted to kg ha^{-1} where soil mass was 2.268×10^6 kg ha^{-1} when BD was 1.35 g cm^{-3} and soil depth was 15 cm. Soil mass was adjusted accordingly for different soil depths and BDs. Total N (kg ha^{-1}) was converted to N mineralization using the decimal fraction of $\%N_{min}$.

The TM correction factor was based on N mineralization in Australian soils (Wang et al., 2003) as described by Gilmour and Mauromoustakos (2011). The TM factor was the ratio of k_{II} at a given temperature and moisture to that at 25˚C and 55% WHC where the TM factor was unity. The SAS JMP PRO 15 Fit Model platform was used to develop the TM factor for k_{II} presented in Eq. 2.

$$TM_{kII} = -0.486 + 0.0286*T + 0.0140*M \ (R^2 = 0.86, RMSE = 0.13) \quad [2]$$

National Oceanic and Atmospheric Administration (NOAA) weather data (monthly air temperature, precipitation, and pan evaporation) were used for field predictions. Since precipitation and pan evaporation are reported in inches, soil moisture calculations were made using depths of water. Table 1 presents the physical data for silt loam soil texture used in estimating soil moisture for 91 cm (36 inches) of soil. Each month soil moisture depth was set to the mean of -33 and -1000 kPa and then increased by the depth of precipitation and decreased by 80% of pan evaporation within the limits of water depths at -33 kPa and -1000 kPa. A typical water release curve for a silt loam was used to determine monthly percent water holding capacity (%WHC) as described by Gilmour (1998). In irrigated situations, %WHC can be increased or irrigation depth added to precipitation.

Table 1. Physical properties the silt loam texture (91 cm depth) used to estimate %WHC.

Soil Property	silt loam
BD	1.5
Porosity, %	43
Θwt at -33 kPa	0.23
Θwt at -1000 kPa	0.08
Θvol at -33 kPa	0.35
Θvol at -1000 kPa	0.11
in water/in soil at -33 kPa	12.42
in water/in soil at -1000 kPa	4.05

Soil temperature was assumed to equal air temperature. The model used a daily time step that allowed N mineralization predictions between two dates. Monthly soil temperature and moisture were used to calculate a monthly TM factor. That TM factor was used for each day in the month.

Model predictions were compared to observed N mineralization in two laboratory studies. Miller et al. (2019) determined N mineralization for 57 soils from six areas in northern California. Intact soil cores were incubated for 10 wks at 25˚C and optimum moisture. Miller et al. (2019) presented bar graphs of N mineralization for soils in each area. Visual interpolation was used to obtain data from those bar graphs. The SAS JMP Pro 15 Distribution platform was used to determine mean observed N mineralization and the 95% confidence intervals (95% CI) for the five areas. One location that had only two soils was not included in the analysis as the 95% CI could not be estimated. Model predictions at 25˚C and 55% WHC were made using mean total N and bulk density from each area for the 30 cm soil depth.

Geisseler et al. (2019) determined N mineralization in 30 cm soil for 30 locations in the Sacramento, North San Joaquin, and South San Joaquin Valleys in northern California. Intact soil cores were incubated for 10 wks at 25˚C and optimum moisture. Observed N mineralization was assumed to follow zero order kinetics (mean was 0.37 mg kg^{-1} d^{-1}). Geisseler et al. (2019) N mineralization predictions in the field were corrected for temperature and moisture. First order model predictions (Eq. 1) used mean monthly temperature and precipitation data from 2014 to 2017 for Davis (Sacramento Valley), Modesto (N San Joaquin Valley), and Five Points (S San Joaquin Valley). Davis mean monthly pan evaporation (2014 to 2017) was used for all locations. Geisseler et al. (2019) reported a soil moisture modifier of about 0.96 during the irrigated growing season so 52% WHC was assumed during that period. Annual and seasonal (125-d from 4/13 to 8/16) predictions were made.

The 1st order model was also used to predict N mineralization in soils cropped to corn in Illinois (Khan et al., 2001). NOAA weather data from Peoria, Illinois was used to estimate TM factors. Soil depth was 30 cm. BD was estimated using typical values for each soil texture. Soils where manure was applied were not used as the application of manure limited response to commercial N fertilizer. Yields for unfertilized soils (US) were determined by solving for US in Eq. 3 which relates US to yields of fertilized soils (FS) and fertilizer response (FR).

$$FR = [(FS - US) \times 100]/US \quad [3]$$

N mineralization predictions were for the 35 to 125-d period after a mid-April planting. Seasonal available N was defined as 1st order model predictions (Eq. 1, k_{II} = 0.00021 d^{-1}) plus N contributions from previous crops alfalfa, *Medicago* sativa (112 kg ha^{-1}) or soybean, *Glycine* max (12 kg ha^{-1}) as described by Gilmour (2009). Seventeen soils were in the data set. Two soils were excluded as outliers (high yield/low total N, low yield/high total N). SAS JMP PRO 15 Fit Model platform was used in regression equations for unfertilized yield versus soil N mineralization.

RESULTS AND DISCUSSION

The Miller et al. (2019) summary data are presented in Table 2. Mean total N and BD ranges were 1.12 to 6.22 g kg^{-1} and 0.71 to 1.45 g cm^{-3}, respectively. N mineralization predictions were within the 95% CI for soils from the Sacramento Valley, Salinas Valley and Tulelake locations. Predicted N mineralization was 7 mg kg^{-1} less than the lower 95% CI for soils from the San Joaquin Valley. Mean predicted and observed N mineralization for San Joaquin Valley, Sacramento Valley, Salinas Valley, and Tulelake soils were 33 and 32 mg kg^{-1}, respectively. Predicted N mineralization values for Delta and Tulelake soils were 56 and 16 mg kg^{-1} more than the mean observed values for those locations, respectively, suggesting that the value of k_{II} (0.00021 d^{-1}) was too large to accurately predict N mineralization for soils with high amounts of more stable soil organic N. Agreement of between predicted and observed values was within 1 mg kg^{-1} for Delta and Tulelake soils using k_{II} equal to 0.0009 and 0.00016 d^{-1}, respectively.

Table 2. Model input data, k_{II}, observed and 95% confidence intervals (CI), and predicted model estimates of N mineralization for soils from five locations in N. California.

Location	**Total N†**	**Bulk Density†**	**k_{II}**	**N Mineralization**		
	g kg^{-1}	g cm^{-3}	d^{-1}	**95% CI**	**Observed**	**Predicted**
					mg kg^{-1}	
San Joaquin Valley	1.16	1.19	0.00021	26 to 34	30	19
Sacramento Valley	1.18	1.28	0.00021	19 to 26	22	19
Salinas Valley	1.12	1.45	0.00021	7 to 29	18	18
Delta	6.22	0.84	0.00021	25 to 63	44	100
Tulelake	4.65	0.71	0.00021	37 to 82	59	75

† Miller et al. (2019)

The Geisseler et al. (2019) summary data are presented in Table 3. Mean total N and BD ranges were 1.11 to 1.24 g kg^{-1} and 1.17 to 1.28 g cm^{-3}, respectively. Geisseler et al. (2019) predicted annual N mineralization was 243 kg ha^{-1} as compared to 220 kg ha^{-1} for the 1st order model (Eq. 1, k_{II} = 0.00021 d^{-1}) used herein. The 95% CI for the Geisseler et al. (2019) predictions was 217 to 269 kg ha^{-1}. The 1st order model mean prediction was within this 95% CI.

Table 3. Model input data, k_{II}, observed, and predicted estimates of N mineralization for soils from Sacramento and San Joaquin Valleys in N. California.

Location	Total N†	Bulk Density†	k_{II}	N Mineralization	
	g kg^{-1}	g cm^{-3}	d^{-1}	Seasonal	Annual
				kg ha^{-1}	
Sacramento Valley	1.18	1.28	0.00021	125	217
N San Joaquin Valley	1.24	1.23	0.00021	141	232
S San Joaquin Valley	1.11	1.17	0.00021	118	201

† Geisseler et al. (2019)

Geisseler et al. (2019) found 49% of annual N mineralization (119 kg ha^{-1}) occurred during the 125-d growing season over all sites. Model seasonal predictions in Table 2 were 118 to 141 kg ha^{-1} for a mean of 128 kg ha^{-1} for the 125-d growing season. This was 58% of the annual value (220 kg ha^{-1}).

The Khan et al. (2001) summary data are given in Table. 4. Total N and BD ranges were 0.61 to 2.03 g kg^{-1} and 1.3 to 1.7 g cm^{-3}, respectively. Predicted annual N mineralization (Eq. 1, k_{II} = 0.00021 d^{-1}) was 87 to 285 kg ha^{-1}. Predicted growing season N mineralization was 47 to 155 kg ha^{-1} with a mean of 107 kg ha^{-1} (95% CI 91 to 124 kg ha^{-1}). Annual predicted N mineralization was 3.0% of SOM N as compared to 2 to 4% reported by Sawyer et al. (2006) for SOM decomposition in the Midwest US Corn Belt. Fifty-two percent of predicted N mineralization occurred during the growing season.

Table 4. Model input data, k_{II}, and N mineralization estimates for soils in Illinois.

# Soil	Total N†	Bulk Density†	k_{II}	N Mineralization	
	g kg^{-1}	g cm^{-3}	d^{-1}	Seasonal	Annual
				kg ha^{-1}	
3 Flanigan sil	1.99	1.4	0.00021	155	285
11 Downs sil	1.61	1.4	0.00021	126	231
12 Drummer sicl	2.03	1.3	0.00021	147	270
13 Varna sil	1.5	1.4	0.00021	117	215
14 Radle sil	1.16	1.4	0.00021	91	166
15 Ipava sil	1.79	1.4	0.00021	140	257
16 Maumee ls	1.22	1.7	0.00021	116	212
17 Cisne sl	1.65	1.4	0.00021	129	237
18 Atterberry sil	0.85	1.4	0.00021	66	122
19 Iva sil	1.32	1.4	0.00021	103	199
20 Bonfield l	1.84	1.4	0.00021	144	264
21 Ipava sil	1.52	1.4	0.00021	119	218
23 Ipava sil	1.51	1.4	0.00021	118	216
24 Cisne sil	1.09	1.4	0.00021	85	156
25 Stronghurst sil	0.61	1.4	0.00021	47	87

† Khan et al. (2001)

Unfertilized corn yields were related to seasonal N mineralization predictions plus N mineralized from the previous crop (Fig. 1). The relationship included soils where corn yields did not respond to commercial N fertilizer additions and soils where a response was found. The slope was equivalent to 32.0 kg grain per kg seasonal available N as compared 67.5 kg grain per kg seasonal available N for commercial N fertilizer applied to soils in the Midwest US Corn Belt (Sawyer et al., 2006). Thus, seasonal N mineralized from SOM and the previous crop residue was 47% as available as commercial fertilizer N (47% N use efficiency). In comparison, Sawyer et al. (2006) estimated 55 to 65% of commercial fertilizer N is absorbed by the corn crop in the Midwest Corn Belt.

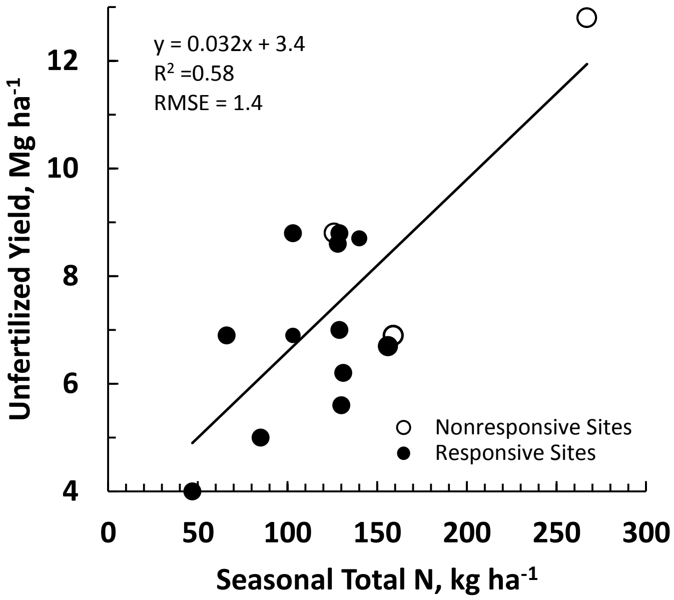

Fig. 1 Unfertilized corn yield versus predicted seasonal total N from SOM plus crop residue N for locations near Peoria, IL.

It is probable that the lack of timing of N mineralization using Eq. 1 (k_{II} = 0.00021 d^{-1}) with typical corn N uptake (Bender et al., 2013) explained the lower N use efficiency of N mineralized from SOM as compared to commercial N fertilizer (Fig. 2). Mean monthly N mineralization (0 to 30 cm) predictions in Fig. 2 used mean BD (1. 4 g cm^{-3}) and total N (1.45 g kg^{-1}) in Table 4 and Peoria, IL weather. Predicted monthly N mineralization was equivalent to N uptake in April and July, but only 26 and 21% of N uptake in May and June, respectively. Over the April to August period cumulative N uptake was 280 kg ha^{-1}, while predicted seasonal N mineralization plus crop residue N was only 40% of that value (113 kg ha^{-1}).

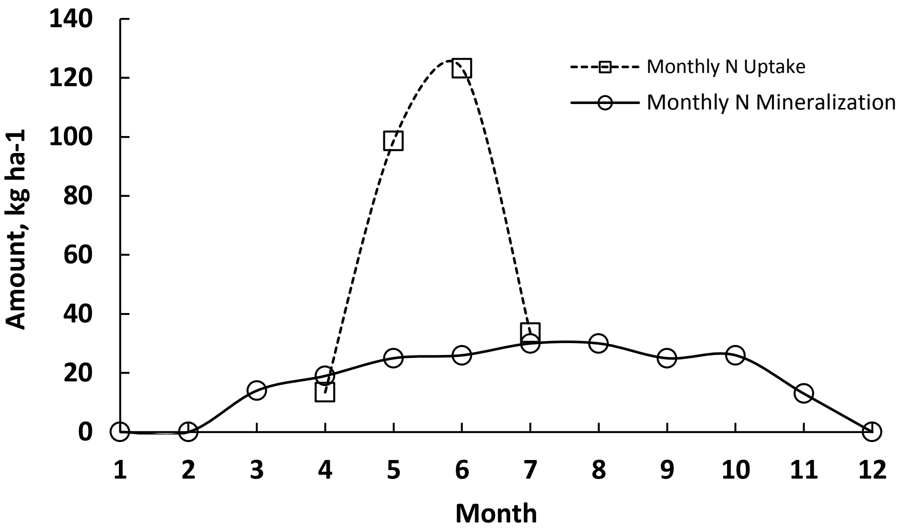

Figure 2. Monthly N uptake and monthly N mineralization for corn grown in Illinois.

Seasonal N mineralization predictions were linearly related to total N as stated by Ros et al. (2011). The equation for corn grown in Illinois is shown below (Eq. 4). This is for 30 cm of soil with a bulk density of 1.3 to 1.7 g cm^{-3}.

N mineralization (kg ha^{-1}) = 7.8 + 73.1 × total N (g kg^{-1}) (R^2 = 0.96, RMSE 6.2) [4]

The intercept was not significantly different from zero. The slope equates to 73.1 kg ha^{-1} SOM N mineralization for each g total N kg^{-1} soil. Equation 4 could substitute for the 1st order model for the Peoria, Illinois area simplifying the prediction of N mineralization for that location.

Table 5 presents the slopes for locations in the five leading corn producing states for a 30 cm soil depth and a BD of 1.4 g cm^{-3} for 2019 weather data. The mean for the five states was 68 kg ha^{-1}/g kg^{-1}, while the 95% CI was 63 to 73 kg ha^{-1}/g kg^{-1} (SAS JMP Pro 15 Distribution platform). The values in Table 5 change with BD and soil depth and are unique for location/soil series combinations. The general equation for predicting seasonal N mineralization is shown below (Eq. 5),

Seasonal N mineralization = slope × Total N × (Depth/30 cm) × (BD/1.4 g cm^{-3}) [5]

where slope is N mineralization per total N (kg ha^{-1}/g kg^{-1}) in Table 5 as determined by the 1st order model (Eq. 1, k_{II} = 0.00021 d^{-1}). This seasonal N mineralization (Eq. 5) should be adjusted for N use efficiency (47%) when used to adjust commercial N fertilizer recommendations. This results in a mean reduction for commercial fertilizer rates of 32 kg ha^{-1}/g kg^{-1}, a value very similar to that in Fig 1.

Table 5. N mineralization per unit of total N where BD = 1.4 g cm^{-3} and soil depth is 30 cm.

Location	Planting	Season	N Mineralization per Total N
			kg ha^{-1}/g kg^{-1}
Sioux City, IA	late April	6/6 - 10/9	70
Ames, IA	late April	6/6 - 10/9	64
Waterloo, IA	late April	6/6 - 10/9	64
Peoria, IL	mid April	5/20 - 10/3	78
Dekalb, IL	mid April	5/20 - 10/3	59
North Platte, NE	late April	6/3 -10/6	78
Omaha, NE	late April	6/3 -10/6	68
Grand Island, NE	late April	6/3 -10/6	53
St. Paul, MN	late April	6/3 - 10/6	65
Lamberton, MN	late April	6/3 - 10/6	58
Evansville, IN	late April	6/3 - 10/6	83
Indianapolis, IN	late April	6/3 - 10/6	71
Fort Wayne, IN	late April	6/3 - 10/6	75

CONCLUSIONS

The 1st order model presented herein provided reasonable estimates of N mineralization for both laboratory and field studies. The model considers the impacts of soil temperature and moisture and has inputs (total N, bulk density, monthly weather) that are readily available or calculable and, so, useful to apply to field studies. Once the predicted seasonal N mineralization for a given soil/location is known, the linear relationship between predicted seasonal N mineralization and total N can be determined. This value should be corrected for N use efficiency. Commercial N fertilizer recommendations can then be adjusted for seasonal N mineralization as well as other N inputs (crop residue, manure, N in precipitation). Future studies should focus on crop yield versus seasonal available N using this approach.

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