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# United States Midwest Soil and Weather Conditions Influence Anaerobic Potentially Mineralizable Nitrogen

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# United States Midwest Soil and Weather Conditions Influence Anaerobic Potentially Mineralizable Nitrogen

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## Core Ideas

- Relationships between mineralization estimates taken with the  $PMN_{an}$  test and soil and weather conditions need to be improved.
- Soil sample timing and N fertilization minimally affected  $PMN_{an}$  predictability by soil and weather parameters.
- Soil properties predict  $PMN_{an}$  better than weather conditions.
- Soil and weather conditions combined explain up to 69% of the variability of  $PMN_{an}$ .
- Longer  $PMN_{an}$  incubations improve the relationship between soil and weather parameters and  $PMN_{an}$  after N fertilization.

Nitrogen provided to crops through mineralization is an important factor in N management guidelines. Understanding of the interactive effects of soil and weather conditions on N mineralization needs to be improved. Relationships between anaerobic potentially mineralizable N ( $PMN_{an}$ ) and soil and weather conditions were evaluated under the contrasting climates of eight US Midwestern states. Soil was sampled (0–30 cm) for  $PMN_{an}$  analysis before pre-plant N application ( $PP_{0N}$ ) and at the V5 development stage from the pre-plant 0 ( $V5_{0N}$ ) and 180 kg N ha<sup>-1</sup> ( $V5_{180N}$ ) rates and incubated for 7, 14, and 28 d. Even distribution of precipitation and warmer temperatures before soil sampling and greater soil organic matter (SOM) increased  $PMN_{an}$ . Soil properties, including total C, SOM, and total N, had the strongest relationships with  $PMN_{an}$  ( $R^2 \leq 0.40$ ), followed by temperature ( $R^2 \leq 0.20$ ) and precipitation ( $R^2 \leq 0.18$ ) variables. The strength of the relationships between soil properties and  $PMN_{an}$  from  $PP_{0N}$ ,  $V5_{0N}$ , and  $V5_{180N}$  varied by  $\leq 10\%$ . Including soil and weather in the model greatly increased  $PMN_{an}$  predictability ( $R^2 \leq 0.69$ ), demonstrating the interactive effect of soil and weather on N mineralization at different times during the growing season regardless of N fertilization. Delayed soil sampling ( $V5_{0N}$ ) and sampling after fertilization ( $V5_{180N}$ ) reduced  $PMN_{an}$  predictability. However, longer  $PMN_{an}$  incubations improved  $PMN_{an}$  predictability from both V5 soil samplings closer to the  $PMN_{an}$  predictability from  $PP_{0N}$ , indicating the potential of  $PMN_{an}$  from longer incubations to provide improved estimates of N mineralization when N fertilizer is applied.

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**Abbreviations:** AWDR, abundant and well-distributed rainfall; first-GDD, first day of the calendar year where temperatures were high enough to calculate a growing degree-day; GDD, growing degree-day;  $PMN_{an}$ , anaerobic potentially mineralizable nitrogen; PP, pre-plant;  $PP_{0N}$ , pre-plant soil sampling where 0 kg N ha<sup>-1</sup> was applied at planting; SDI, Shannon diversity index; SOM, soil organic matter;  $V5_{0N}$ , V5 soil sampling where no N was applied at planting;  $V5_{180N}$ , V5 soil sampling where 180 kg N ha<sup>-1</sup> was applied at planting.

**N**itrogen is needed for optimal growth and development of crops. The ability of the soil to supply N to corn (*Zea mays* L.) can vary from 20 to 100% of crop N needs (Khan et al., 2001; Ros et al., 2011; Yost et al., 2012). This wide range in N mineralization potential demonstrates the need to better estimate the contribution of N mineralization to crop N requirements. An improvement in the estimate of N mineralization would likely lead to improved fertilizer N rate guidelines and fertilizer N use efficiency. This improvement in fertilizer N rate guidelines would lower the potential for underfertilization, which reduces yield and profit, and overfertilization, which also reduces profits and is associated with negative environmental effects (Ribaud et al., 2011).

Although there are many soil biological and chemical indices that are used to estimate N mineralization (Schomberg et al., 2009; Stanford and Smith, 1972; Wade et al., 2016), the two standard biological mineralization indices are the aerobic (Stanford and Smith, 1972) and anaerobic potentially mineralizable N ( $PMN_{an}$ ) (Keeney and Bremner, 1966; Waring and Bremner, 1964) tests. The aerobic test is traditionally considered the benchmark mineralization test by which other tests are compared. However, the aerobic and  $PMN_{an}$  tests have been shown to be highly correlated in both forest and agricultural soils (Mariano et al., 2013; Smith et al., 1981; Waring and Bremner, 1964). The  $PMN_{an}$  test is now used more often for routine analysis because it is cheaper, has a shorter turnaround, and measures only  $NH_4-N$  (Bundy and Meisinger, 1994; Waring and Bremner, 1964). The  $PMN_{an}$  test quantifies N mineralization by incubating saturated soils at 40°C for 7 d and measuring the net amount of  $NH_4-N$  produced.

The  $PMN_{an}$  test has been successfully used as an N mineralization estimate in Argentina to improve relative yield predictability and the accuracy of soil tests, such as the pre-plant and pre-sidedress nitrate tests, which are used to make N fertilizer application decisions (Orcellet et al., 2017; Sainz Rozas et al., 2008). Other studies in the northwestern and southeastern areas of the United States have successfully related  $PMN_{an}$  to the N response of winter wheat and the economic optimal N rate of corn (Christensen et al., 1999; Williams et al., 2007). These results indicate that  $PMN_{an}$  has the potential to improve the accuracy of N recommendation systems in the US Midwest. An understanding of the variability of  $PMN_{an}$  in the contrasting soil and weather conditions of the US Midwest would aid in determining the potential use of  $PMN_{an}$  as an estimate of N mineralization to improve the accuracy of N recommendations.

The amount of N mineralized in a growing season is dependent on the size and quality of the organic N pool (Sierra, 1992; Wu et al., 2008). The rate at which the organic N pool then de-

composes depends on air and soil temperature, soil moisture (Cabrera et al., 2005; Kuzyakova et al., 2006; Wu et al., 2008), and tillage (Beyaert and Voroney, 2011; Mikha et al., 2006). Many studies have examined the effects of crop rotation (Carrington et al., 2012; Gentile et al., 2011; Grandy and Neff, 2008; Parton et al., 2007), tillage (Beyaert and Voroney, 2011; Mikha et al., 2006), and cover cropping practices (Kuo and Sainju, 1998; Melkonian et al., 2017) on N mineralization, but fewer have examined the effect of soil properties and weather patterns on N mineralization.

In previous studies, soil properties such as cation exchange capacity, total organic C, and total N were correlated to mineralizable N (Fox and Piekielek, 1984; Narteh and Sahrawat, 1997; Schomberg et al., 2009; Soon et al., 2007). In contrast, other studies found no relationship between N mineralization and total organic C or soil organic matter (SOM) (Mariano et al., 2013; Reussi Calvo et al., 2013; Sainz Rozas et al., 2008). Soil texture class has also been shown to have a relationship with N mineralization, with sand having a negative relationship and clay a positive relationship (Dessureault-Rompré et al., 2010; Ladd et al., 1996). Greater clay content can be associated with greater N mineralization because of its ability to physically protect organic matter from decomposition (Hassink et al., 1993). In contrast, soil microbial biomass is typically more active in a coarse-textured soil relative to a fine-textured soil (Franzluebbers et al., 1996). Overall, these soil properties are related to the structure of the soil and its ability to exchange gas and retain moisture that is needed for the microbially mediated process of N mineralization (Van Veen and Kuikman, 1990).

Weather is also an important factor in N mineralization. The amount of N mineralization has been shown to increase with temperature in both laboratory and field studies (Fernández et al., 2017; Kuzyakova et al., 2006; Sierra, 1996; Wu et al., 2008). Precipitation also influences N mineralization. Specifically, low precipitation and soil moisture are often related to differing patterns and lower amounts of N mineralization (Kuzyakova et al., 2006). Precipitation events that rewet the soil throughout the growing season also stimulate increases in N mineralization more so than a single precipitation event (Murphy et al., 1998; Wu et al., 2008). Furthermore, N mineralization has been found to be at its highest when temperatures are maximal and soil moisture is slowly decreasing (Kuzyakova et al., 2006). There is also an interactive effect of temperature and precipitation on N mineralization that varies by soil texture and location of the soil in the landscape. For example, soils with low organic matter and clay content have the strongest N mineralization response to temperature and precipitation changes. On the other hand, soils with greater clay content and organic matter have shown weaker responses to changes in temperature and precipitation, likely due to the ability of clay and organic matter to buffer the influence of changes in environmental conditions (Kuzyakova et al., 2006).

Few studies have examined the influence of weather/climate and soil texture across a large geographical area to determine their influence on mineralization. One such study that spanned across North America determined that the macroclimate (temperature and precipitation regime) had a significant effect on the amount

of SOM that was available for decomposition (Franzluebbers et al., 2001). In addition, greater mean annual temperatures resulted in more mineralization, whereas the influence of precipitation on mineralization varied based on the temperature regime. In a study with soils across Canada, Dessureault-Rompré et al. (2010) determined soil properties alone can explain up to 40% of the variability in mineralization, whereas climate predictors explained only up to 24%. By combining soil and climate parameters in a multiple regression, the explained variation in mineralization increased to 63%. The US Midwestern Cornbelt region has varying weather and soil conditions that likely influence N mineralization. For example, as summarized by Kitchen et al. (2017), mean annual precipitation increases from the northwest (223–519 mm) to the southeast (92–1157 mm), and mean annual temperature increases from the north (−0.7 to 5.4°C) to the south (13.9–18.2°C). These temperature differences lead to a growing season duration of ~90 d in the north and up to 120 d in the south. The soils in the US Midwest region that are important to agriculture are diverse and dominated by Alfisols, Mollisols, and Entisols. However, the relationships between  $PMN_{an}$  and these contrasting soil texture and weather conditions in the US Midwestern Cornbelt region alone or combined have not been studied at length.

The relationship between soil and weather parameters and mineralization values have typically been examined on soil samples taken in the spring before fertilization. However, it has recently been shown that soil sample collection timing, N fertilization, and the incubation period of the  $PMN_{an}$  test can affect  $PMN_{an}$  by increasing or decreasing it, depending on soil properties and the weather conditions before sampling (Clark, 2018; Culman et al., 2013). The relationship between soil properties and weather conditions and  $PMN_{an}$  from different sample timings, N fertilization rates, and different incubation lengths has not been investigated. The influence of N fertilization and soil sample collection timing on  $PMN_{an}$  is especially important in the corn production areas of the US Midwest. Nitrogen fertilizer application is important because it is applied to most corn production fields and has been reported to alter the amount and variability of N mineralization, depending on the quality of the organic N and soil texture (Chen et al., 2014; Conde et al., 2005; Fernández et al., 2017; Ma et al., 1999). This increased variability may lower the utility of the  $PMN_{an}$  test obtained from soil samples taken before fertilization to provide N recommendations when fertilizer is either all applied near-planting or split into two or more applications throughout the season. Soil sample timing is important because N mineralized in the early spring is highly susceptible to loss in the US Midwest from denitrification and leaching processes due to greater spring precipitation and less N uptake by corn until it reaches the V5-V6 development stage (Randall and Vetsch, 2005; Ritchie et al., 1996; Struffert et al., 2016). This later uptake timing of corn indicates that an N mineralization estimate closer to the high N uptake period of corn may be a more accurate estimate of N available for uptake by the corn crop. Thus, the objective of this research was to determine the effect of soil and weather information across a range of environmental conditions within the US Midwestern Corn Belt on  $PMN_{an}$  predictability.

## MATERIALS AND METHODS

### Experimental Design

Thirty-two study sites were selected in eight US Midwestern states (Illinois, Indiana, Iowa, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin). Maps and tables with information on soil classification and physical and chemical characteristics, precipitation, temperature, and other site descriptions along with details on the uniform treatments, measurement methodologies, and agronomic practices used across all sites were presented by Kitchen et al. (2017). A standard research protocol was used at all experimental sites that included the same treatments and measurement methodology. The research protocol, along with specific details regarding agronomic practices, is described in Kitchen et al. (2017). Briefly, two sites were selected in each state in 2014 and 2015 (32 site-years total). A randomized complete block design with four replications was used at each experimental site. Nitrogen rates selected for this study consisted of an unfertilized check and an N rate of 180 kg N ha<sup>-1</sup> applied at planting, which was considered the N rate that would typically optimize corn grain yield. These two N rates were a subset of the eight N rates applied in this study (0–315 kg N ha<sup>-1</sup> in increments of 45 kg N ha<sup>-1</sup> applied as a single application near planting and split between two timings). Nitrogen as ammonium nitrate (34–0–0, N–P–K) was broadcast-applied and left on the soil surface.

### Soil Sampling

At each site before planting and fertilization, two soil cores were obtained from each replication (120-cm depth; 3.8–4.0 cm i.d.) and divided by horizons to measure physical and chemical properties. These soil properties included a taxonomic description, bulk density (bulk density–measured), total C, total organic C, SOM, total N, cation exchange capacity, and pH (1:1 soil/water pH and 1:1 soil/salt [1 M KCl] pH) as described in Kitchen et al. (2017). Soil texture and SOM measurements were used to calculate Saxton bulk density (bulk density–Saxton) (Saxton and Rawls, 2006). We calculated weighted averages for the various soil measurements using the depth of each horizon within the 0- to 30-cm soil depth.

The  $PP_{0N}$  soil samples were obtained using a 10-core (0- to 30-cm, 30- to 60-cm, and 60- to 90-cm soil depths; 1.9 to 4.0 cm i.d.) composite soil sample before planting and fertilization. At the V5 corn development stage, a six-core composite (0 to 30- and 30 to 60-cm soil depths; 1.9 cm i.d.) soil sample was obtained from the 0 ( $V5_{0N}$ ) and at-planting 180 ( $V5_{180N}$ ) kg N ha<sup>-1</sup> treatments. All soil samples were dried ( $\leq 32^\circ\text{C}$ ) and ground to pass through a 2-mm sieve. Soil  $\text{NO}_3\text{-N}$  was extracted using 0.2 M KCl (Saha et al., 2018) and quantified by the cadmium reduction method (Gelderman and Beegle, 2015) with a modified Technicon AutoAnalyzer (SEAL Analytical, Inc.). Only the surface soils (0–30 cm depth in this study) were analyzed for  $PMN_{an}$  to maintain consistency with depth used when the  $PMN_{an}$  test was originally developed (Bundy and Meisinger, 1994).

To determine  $PMN_{an}$ , 20 mL of ultrapure water was placed on top of 4.0 g of soil in 50-mL Falcon tubes (Corning Inc.). The



**Table 1. Weather variables used and their definitions.**

Weather parameter	Definition
Mean minimum temperature	Tmin = minimum daily temperature
Mean maximum temperature	Tmax = maximum daily temperature
Mean temperature	MeanTemp = (Tmax + Tmin)/2
Growing degree-days	GDD = [(Tmax + Tmin)/2] - 10°C, where Tmax = Tmax if 10 ≤ Tmax ≤ 30, if Tmax ≤ 10 then Tmax = 10, if Tmax ≥ 30 then Tmax = 30; Tmin = the minimum daily temperature if Tmin ≥ 10, if Tmin ≤ 10 then Tmin = 10; all temperatures measured in °C
Sum of precipitation	SP = Σ(Rain), where rain is the daily precipitation (mm)
Mean precipitation	MaxP = SP/n, where n is the number of days in that period
Maximum precipitation	MaxP = maximum amount of rain in a single day in that period
Shannon diversity index	SDI = [-Σpi ln(pi)]/ln(n), where pi = rain/SP is the fraction of daily precipitation relative to the total precipitation in a given time period, and n is the number of days in that period. SDI = 1 implies complete evenness (i.e., equal amounts of precipitation in each day of the period); SDI = 0 implies complete unevenness (i.e., all rain in 1 d)
Abundant and well-distributed rainfall AWDR = SP(SDI)	

tubes were capped and subjected to incubation for 7, 14, and 28 d at 40°C (Keeney and Bremner, 1966). Twenty milliliters of 4 M KCl was added to the solution after incubation for a final extractant concentration of 2 M KCl, and samples were shaken for 30 min. The solution was then passed through a washed 0.45-µm syringe filter disk and stored in a microtube at -80°C until NH<sub>4</sub>-N analysis. The Berthelot method was then used to determine extracted NH<sub>4</sub>-N (Rhine et al., 1998) using a Glomax-Multi Detection System plate reader (Promega Biosystems, Inc.). The initial NH<sub>4</sub>-N value before incubation was also determined for each soil sample following the above extraction procedure with 2 M KCl and subtracted from the NH<sub>4</sub>-N postincubation value to obtain net NH<sub>4</sub>-N produced or PMN<sub>an</sub>.

## Weather

Weather data were collected during the growing season from each experimental site with a HOBO U30 automatic weather station (Onset Computer Corp.). Precipitation and air temperature measurements at ~1.8 m above the ground were recorded every 5 min and used to calculate the daily minimum, maximum, and mean air temperatures and the daily cumulative precipitation. Water provided as irrigation in four of the 32 experimental sites was treated as natural precipitation in these calculations. These daily weather measurements were quality checked by comparing the weather station measurements against interpolated temperature data from Multi-Radar/Multi-Sensor precipitation data (The National Severe Storms Lab, NOAA) as described in Kitchen et al. (2017). Table 1 shows the equations used to calculate growing degree-days (GDDs), mean precipitation, Shannon diversity index (SDI) following Bronikowski and Webb (1996), and abundant and well-distributed rainfall (AWDR) following Tremblay et al. (2012) for different periods during the growing season. The first GDD of the year (first-GDD) was calculated by determining the first day of the calendar year where temperatures were high enough to calculate a GDD.

## Statistical Analysis

Statistical analyses were conducted with SAS software version 9.4 (SAS Institute Inc.). Correlations within soil, precipita-

tion, and temperature variables were determined using PROC CORR. The relationship between PMN<sub>an</sub> and weather measurements and site characteristics were determined using PROC REG. Linear and quadratic models were evaluated. The highest-order model with a *P* value ≤ 0.05 was selected. The *R*<sup>2</sup> value from the simple, linear model was displayed if both linear and quadratic models were not significant ( $\alpha = 0.05$ ). The *R*<sup>2</sup> values of these models were compared to determine whether altering PMN<sub>an</sub> sample timing (PP<sub>0N</sub> vs. V5<sub>0N</sub>) or N rate (V5<sub>0N</sub> vs. V5<sub>180N</sub>) or increasing incubation time (7, 14, and 28 d) improved the relationship between PMN<sub>an</sub> and soil and weather variables.

The stepwise, forward, backward, and Mallows' *C*<sub>p</sub> (Mallows, 1973) selection methods within the REG procedure were used to determine the best combination of soil, precipitation, and temperature variables to predict PMN<sub>an</sub> and how frequently each of these variables was selected. The contributions of temperature and precipitation at defined time intervals were compared for their ability to improve the prediction of PMN<sub>an</sub>. Two intervals were evaluated for the PP<sub>0N</sub> soil sampling, and four intervals were evaluated for the V5 soil sampling. The time intervals for the PP<sub>0N</sub> sampling were (i) first-GDD to PP<sub>0N</sub> and (ii) 30 d before PP<sub>0N</sub>. The time intervals for the V5 sample timings were (i) first-GDD to V5, (ii) 30 d before PP<sub>0N</sub> to V5, (iii) PP<sub>0N</sub> to V5, and (iv) 30 d before V5. Only the weather period for each PMN<sub>an</sub> sample timing (pre-plant and V5) that contributed the most to predicting PMN<sub>an</sub> is shown in this paper.

## RESULTS AND DISCUSSION

Collecting soil samples from fields across eight states in the US Midwest resulted in a wide range of soil properties (Table 2) and weather conditions before soil sampling (Table 3). These differences in soil properties and weather conditions led to PMN<sub>an</sub> values ranging from 0.2 to 99.9 mg N kg<sup>-1</sup> for the 7-d incubations, 2.1 to 122.7 mg N kg<sup>-1</sup> for the 14-d incubations, and 4.0 to 136.7 mg N kg<sup>-1</sup> for the 28-d incubations. The PMN<sub>an</sub> range of other studies in the United States (12–87 mg N kg<sup>-1</sup>) fell within the approximate range of the values found in this study (Christensen and Mellbye, 2006; Fox and Piekielek, 1984). However, this study did have PMN<sub>an</sub> values below those of these

other studies, likely due to the low organic matter content of some of the soils evaluated in conjunction with the deeper sampling depth. The wide range in soil and weather conditions along with PMN<sub>an</sub> created an optimal database to determine relationships between PMN<sub>an</sub> and soil and weather parameters.

### Relationship between Anaerobic Potentially Mineralizable N and Soil Properties

Soil properties, other than soil NO<sub>3</sub>-N and NH<sub>4</sub>-N, produced better relationships with PMN<sub>an</sub> compared with weather variables (mean  $R^2 = 0.19$ ; range, 0.03–0.41) (Table 4). Cation exchange capacity, total C, total organic C, SOM, total N, and bulk density were the soil properties that had the best relationships with PMN<sub>an</sub> ( $R^2 = 0.25$  when averaged across all PMN<sub>an</sub> measurements). Except for bulk density, these properties had a positive relationship with PMN<sub>an</sub>, likely because they directly or indirectly measure the size of the organic N pool, which influences mineralizable N (Cabrera et al., 2005; Mikha et al., 2006; O'Leary et al., 2002; Wu et al., 2008). Previous research has reported similar positive relationships between PMN<sub>an</sub> and cation exchange capacity (Narteh and Sahrawat, 1997), total organic C (Fox and Piekielek, 1984; Narteh and Sahrawat, 1997; Schomberg et al., 2009; Soon et al., 2007), and total N (Fox and Piekielek, 1984; Soon et al., 2007; Schomberg et al., 2009), whereas others have reported no relationship between PMN<sub>an</sub> and total organic C (Mariano et al., 2013; Sainz Rozas et al., 2008) or SOM (Reussi Calvo et al., 2013). The contrasting results among studies may be related to differences in the amount of mineral-associated C versus the particulate-organic C that makes up the total organic C content of soil (Reussi Calvo et al., 2013). Particulate-organic C is normally greater in coarse-textured soils (Divito et al., 2011) and has a better relationship with mineralizable N compared with mineral-associated organic C, which is predominant in fine-textured soils (Studdert et al., 2006). Thus, the inclusion of more coarse-textured soils in our study compared with other studies likely improved the relationship between PMN<sub>an</sub> and total organic C. The lack of correlation between PMN<sub>an</sub> and total organic C in some of these other studies may also be the result of

**Table 2. Minimum, maximum, mean, standard deviation, and coefficient of variation of anaerobic potentially mineralizable N (PMN<sub>an</sub>) and soil properties across 32 site-years.**

Property†	Min.	Max.	Mean	SD	CV
PMN <sub>an</sub> , mg N kg <sup>-1</sup>					
PP <sub>0N</sub> , 7 d	0.7	84.0	26.7	15.1	56.8
PP <sub>0N</sub> , 14 d	2.4	94.5	37.8	18.9	50.0
PP <sub>0N</sub> , 28 d	6.0	125.3	48.9	25.4	51.9
V5 <sub>0N</sub> , 7 d	0.2	99.9	28.3	15.0	53.1
V5 <sub>0N</sub> , 14 d	2.1	122.7	37.0	17.4	47.0
V5 <sub>0N</sub> , 28 d	4.0	136.7	48.5	23.2	47.8
V5 <sub>180N</sub> , 7 d	0.9	92.2	23.2	15.2	65.4
V5 <sub>180N</sub> , 14 d	6.9	109.9	32.4	17.5	53.9
V5 <sub>180N</sub> , 28 d	8.1	130.7	43.1	23.6	54.7
Soil properties					
Sand, %	2	93	26	25	95
Silt, %	4	79	50	19	39
Clay, %	2	61	24	11	47
BD-measured, g cm <sup>-3</sup>	0.95	1.66	1.37	0.13	9.78
BD-Saxton, g cm <sup>-3</sup>	1.07	1.60	1.34	0.13	9.98
TC, g kg <sup>-1</sup>	4.4	55.5	14.6	7.6	51.8
TOC, g kg <sup>-1</sup>	4.4	47.8	14.2	6.9	48.5
SOM, g kg <sup>-1</sup>	7.7	71.0	25.7	10.0	38.9
Total N, g kg <sup>-1</sup>	0.4	4.3	1.4	0.6	41.8
C/N, g kg <sup>-1</sup>	7.2	12.7	10.0	1.0	10.4
CEC, cmol kg <sup>-1</sup>	3	44	20	9	46
pH-salt	4.4	7.8	6.1	0.8	13.6
pH-water	5.1	8.8	6.7	0.8	11.4
Soil-N at PP <sub>0N</sub> , mg kg <sup>-1</sup>					
Ammonium 0–30 cm	3	19	8	4	44
Nitrate 0–30 cm	1	18	6	3	53
Nitrate 0–60 cm	1	12	5	2	42
Nitrate 0–90 cm	1	9	4	2	40
Soil-N at V5 <sub>0N</sub> , mg kg <sup>-1</sup>					
Ammonium 0–30 cm	1	14	7	3	47
Nitrate 0–30 cm	3	27	8	4	58
Nitrate 0–60 cm	2	21	7	4	49
Soil-N at V5 <sub>180N</sub> , mg kg <sup>-1</sup>					
Ammonium 0–30 cm	2	34	9	5	63
Nitrate 0–30 cm	7	75	32	12	38
Nitrate 0–60 cm	9	58	24	9	35

† BD, bulk density; CEC, cation exchange capacity; PP<sub>0N</sub>, PMN<sub>an</sub> from pre-plant soil sampling with 0 kg N ha<sup>-1</sup>; SOM, soil organic matter; TC, total C; TOC, total organic C; V5<sub>0N</sub>, PMN<sub>an</sub> from V5 corn development stage with 0 kg N ha<sup>-1</sup>; V5<sub>180N</sub>, PMN<sub>an</sub> from V5 corn development stage with 180 kg N ha<sup>-1</sup> applied at planting.

**Table 3. Minimum, maximum, mean, standard deviation, and coefficient of variation of precipitation and temperature conditions for the period of 30 d before pre-plant (PP) sampling time to PP and from the PP soil sampling time to the V5 corn development stage across 32 site-years.**

Parameter†	30 d before PP to PP					PP to V5				
	Min.	Max.	Mean	SD	CV	Min.	Max.	Mean	SD	CV
Precipitation										
Maximum, mm	0.30	63	22	17	76	19	95	39	18	46
Sum of precipitation, mm	0.60	250	72	58	80	85	331	175	68	39
Mean, mm	0.02	8	2	2	80	2	5	3	0.6	17
SDI	0.05	0.7	0.5	0.2	34	0.5	0.7	0.6	0.05	8
AWDR	0.12	155	42	37	87	47	242	110	47	43
Temperature										
Mean maximum, °C	9	18	14	3	21	19	27	22	2	8
Mean minimum, °C	-7	7	0.5	4	903	6	13	10	2	1
Mean, °C	2	13	7	3	48	13	20	16	2	10
GDD	43	147	84	30	36	228	543	347	84	24

† AWDR, abundant and well-distributed rainfall; GDD, growing degree-day; SDI, Shannon diversity index.

large C/N ratios causing N to be immobilized instead of mineralized, leading to reduced correlations with  $PMN_{an}$  (Mariano et al., 2013). Unlike the previously discussed soil properties, bulk density had a negative relationship with  $PMN_{an}$  (Table 4) because soils with greater bulk densities in this study were sandy and had less SOM and total N (Table 5), which decreases mineralizable N potential (Dessureault-Rompré et al., 2010). Soils with greater bulk density can also reduce mineralization by limiting microbial access to organic N (Beare et al., 2009).

Soil texture properties (sand, silt, and clay) had a weaker relationship with  $PMN_{an}$  (average  $R^2 = 0.12$ ) compared with the previously discussed soil properties (Table 4). Other studies have

reported similarly poor relationships between  $PMN_{an}$  and sand, silt, and clay content (Dessureault-Rompré et al., 2010; Mariano et al., 2013). On average, the predictability of  $PMN_{an}$  was less for silt ( $R^2 = 0.05$ ) relative to sand ( $R^2 = 0.13$ ) and clay ( $R^2 = 0.15$ ) because sand and clay, compared with silt content, relate better to total N and SOM (Table 5), which is strongly associated with  $PMN_{an}$  (Table 4). There was a positive relationship between  $PMN_{an}$  and clay and silt content because soils with greater silt and clay had more SOM (Table 5), which relates to greater  $PMN_{an}$  (Table 4). More SOM and potentially mineralizable N also occurred in soils with greater clay content because clay particles can physically protect organic N from microbial decomposition,

**Table 4. Coefficients of determination of the anaerobic potentially mineralizable N soil test ( $PMN_{an}$ ) from soil samples obtained before planting and N fertilizer application ( $PP_{0N}$ ) and at the V5 development stage where zero ( $V5_{0N}$ ) or 180 kg N ha<sup>-1</sup> ( $V5_{180N}$ ) was applied at planting and incubated for 7, 14, and 28 d as a function of soil properties, precipitation, and temperature variables across 32 site-years.**

Variable†	$PP_{0N}$			$V5_{0N}$			$V5_{180N}$		
	7 d	14 d	28 d	7 d	14 d	28 d	7 d	14 d	28 d
	$R^2$								
Soil physical characteristics									
% Sand	0.13*N‡	0.21*N	0.20*	0.08*N	0.16*N, Q§	0.19*N	0.02	0.06*N	0.11*N
% Silt	0.05*	0.10*	0.08*	0.03	0.07*	0.09*	<0.01	0.01	0.03
% Clay	0.14*	0.18*	0.21*	0.12*	0.14*	0.20*	0.06*	0.14*	0.19*
BD-measured	0.20*N	0.20*N	0.26*N	0.14*N	0.16*N	0.26*N	0.09*N	0.14*N	0.23*N
BD-Saxton	0.19*N	0.28*N	0.29*N	0.22*N	0.24*N	0.36*N	0.15*N	0.24*N	0.34*N
Soil chemical characteristics									
TC	0.30*	0.29*Q	0.37*Q	0.17*	0.19*	0.24*	0.24*Q	0.29*	0.39*
TOC	0.31*	0.30*Q	0.38*Q	0.16*	0.18*	0.25*	0.24*N, Q	0.29*	0.40*
SOM	0.29*	0.30*	0.37*Q	0.12*	0.16*	0.25*	0.22*N, Q	0.30*N, Q	0.37*
TN	0.33*	0.30*	0.40*Q	0.17*	0.20*	0.27*	0.22*N, Q	0.26*	0.38*
C/N	0.10*	0.08*	0.11*	0.05*	0.03*	0.05*	0.12*	0.15*	0.17*
CEC	0.23*	0.22*	0.26*	0.16*	0.18*	0.24*	0.12*	0.22*	0.28*
pH-salt	0.14*	0.06*	0.06*	0.22*N, Q	0.17*N, Q	0.16*N, Q	0.17*N, Q	0.18*N, Q	0.19*N, Q
pH-water	0.13*	0.05*	0.05*	0.08*N, Q	0.08*N, Q	0.06*N, Q	0.09*	0.10*N, Q	0.10*N, Q
Inorganic N¶									
NH <sub>4</sub> -N§ 0–30 cm	0.06*N, Q	0.01	0.07*	0.01	0.06*Q	0.08*Q	<0.01	0.04*Q	0.03
NO <sub>3</sub> -N§ 0–30 cm	0.01	0.02	0.01	<0.00	0.01	0.02	0.02	<0.01	<0.01
NO <sub>3</sub> -N 0–60 cm	0.04*	0.06*	0.05*	0.01	0.03	0.04*	0.01	<0.01	<0.01
NO <sub>3</sub> -N 0–90 cm	0.07*	0.08*	0.06*						
Precipitation#									
Maximum	0.02	0.03	0.02	0.05*N	<0.01	<0.01	0.01	0.01	<0.01
Sum of precipitation	0.01	0.01	0.01	0.13*Q	0.16*Q	0.16*Q	<0.01	0.08*Q	0.08*Q
Mean	0.01	0.01	0.01	0.01	<0.01	<0.01	0.05*N, Q	0.05*N, Q	<0.01
SDI	0.10*Q	0.12*Q	0.09*Q	0.09*Q	0.02	0.05*	0.01	0.01	0.02
AWDR	0.01	0.01	0.01	0.16*Q	0.18*Q	0.18*Q	<0.01	0.06*Q	0.06*Q
Temperature#									
Mean maximum	0.05*Q	0.06*Q	0.10*Q	0.11*N	0.06*N	0.08*N	0.07*N	0.11*N	0.11*N
Mean minimum	0.15*Q	0.19*Q	0.20*Q	0.04*N	0.01	0.02	0.04*N	0.07*N	0.06*N
Mean	0.12*Q	0.15*Q	0.17*Q	0.08*N	0.04*N	0.05*N	0.06*N	0.10*N	0.09*N
GDD	0.02	<0.01	0.07*Q	0.04*Q	0.04*Q	0.03*Q	0.01	0.04*Q	0.01

\* Significant at the  $P \leq 0.05$  level.

† AWDR, abundant and well-distributed rainfall; BD, bulk density; CEC, cation exchange capacity; GDD, growing degree-day; SDI, Shannon diversity index; SOM, soil organic matter; TC, total C; TN, total N; TOC, total organic C.

‡ N, the linear part of the relationship with  $PMN_{an}$  was negative.

§ Q, these models had a quadratic relationship with  $PMN_{an}$ .

¶ NO<sub>3</sub>-N and NH<sub>4</sub>-N measured in treatment and at timing of  $PMN_{an}$  sampling.

# Period used when regressing precipitation and temperature variables: for  $PP_{0N}$ , first-GDD to pre-plant sampling;  $V5_{0N}$  and  $V5_{180N}$ , pre-plant sampling to V5 corn development stage.



leading to a larger pool of organic N available to be mineralized (Dessureault-Rompré et al., 2010; Hassink et al., 1993). There was a negative relationship between  $PMN_{an}$  and sand content because greater sand content was related to less SOM and total N (Table 5), which reduces N mineralization (Dessureault-Rompré et al., 2010). The reduced capacity of sandy soils to protect organic matter from microbial decomposition hinders the accumulation of organic N that increases  $PMN_{an}$  (Hassink et al., 1993).

The relationship between  $PMN_{an}$  and pH-water and pH-salt was similar to that of soil texture properties (average  $R^2 = 0.12$ ) (Table 4). The pH-salt measurement had a marginally (8–14%) better relationship with  $PMN_{an}$  from the V5 soil samplings compared with pH-water, whereas their relationship was similar with  $PMN_{an}$  from the pre-plant sampling time. The relationship between both pH measurements and  $PMN_{an}$  varied by time of sampling. The  $PP_{0N}$   $PMN_{an}$  timing had a positive linear response to increasing pH-salt and pH-water, whereas the  $PMN_{an}$  from  $V5_{0N}$  and  $V5_{180N}$  had a negative quadratic response below pH 6.0 and a positive quadratic response at  $pH \geq 6.0$ . A reduction in N mineralization as pH decreased agrees with previous studies (Adams and Martin, 1984; Motavalli et al., 1995; Narteh and Sahrawat, 1997; Paul et al., 2001), whereas other investigators reported no relationship (Curtin et al., 1998; Dessureault-Rompré et al., 2010). However, there was a significant relationship between pH and the amount of mineralizable N in the Dessureault-Rompré et al. (2010) study in the first 2 wk of a 24-wk aerobic incubation. This relationship suggests that pH is more related to the labile pools of mineralizable N relative to the stable pools, indicating  $PMN_{an}$  might be measuring a more labile pool of mineralizable N.

The relationships between pre-plant and V5 soil inorganic-N and  $PMN_{an}$  were poor ( $R^2 \leq 0.09$ ) (Table 4). Others have also reported little to no significant relationship between mineralizable N and soil inorganic-N (Fox and Piekielek, 1984; Mariano et al., 2013; Reussi Calvo et al., 2013). The poor correlation between soil inorganic-N and  $PMN_{an}$  was likely because  $NH_4-N$  nitrifies quickly, and soil  $NO_3-N$  can move deeper in the soil profile via leaching or volatilize via denitrification. Leaching and denitrification are dependent on weather and soil management practices (Divito et al., 2011) that varied across sites and years in our study

and may be the cause of the low correlation between  $PMN_{an}$  and inorganic-N. Because inorganic-N was not a good predictor of  $PMN_{an}$ , these measurements will not be included in the remaining discussions regarding soil properties unless explicitly mentioned.

### Relationship between Anaerobic Potentially Mineralizable N and Weather Prior to Soil Sampling

When relating  $PMN_{an}$  from  $PP_{0N}$  to weather conditions before the soil sampling, the weather conditions during the 30 d before  $PP_{0N}$  had a greater partial  $R^2$  in two of the three incubation times and a greater average partial  $R^2$  (0.12) across all three incubation times relative to the first-GDD to  $PP_{0N}$  time interval (partial  $R^2 = 0.09$ ; data not shown). For  $PMN_{an}$  from  $V5_{0N}$  and  $V5_{180N}$ , the weather conditions during the  $PP_{0N}$  to V5 (0.09) time interval had the strongest relationship, as measured by partial  $R^2$  (averaged across all three incubation lengths) followed by first-GDD of the year to V5 (0.07), 30 d before  $PP_{0N}$  to V5 (0.03), and 30 d before V5 (0.05) time intervals (data not shown). Based on these analyses, we present only weather data for the 30 d before  $PP_{0N}$  time interval for  $PMN_{an}$  from  $PP_{0N}$  and the  $PP_{0N}$  to V5 time interval for  $PMN_{an}$  from  $V5_{0N}$  and  $V5_{180N}$  when relating precipitation and temperature measurements to  $PMN_{an}$ .

Excluding GDD, temperature variables from the 30 d before  $PP_{0N}$  interval had the best relationships with  $PMN_{an}$  from  $PP_{0N}$  ( $R^2 \leq 0.20$ ), whereas all temperature variables from the  $PP_{0N}$  to V5 period had a slightly weaker relationship with  $PMN_{an}$  from  $V5_{0N}$  and  $V5_{180N}$  ( $R^2 \leq 0.11$ ) (Table 4). There was a negative relationship between temperature and each  $PMN_{an}$  sample timing and N rate. This negative relationship likely illustrates that, with warmer temperatures, greater mineralization of easily mineralizable materials may have occurred early in the season (before V5) (Kuzyakova et al., 2006), leaving more recalcitrant materials for mineralization from samples obtained at the V5 soil sample timing. The SDI was the only precipitation variable that had a significant relationship with  $PMN_{an}$  from  $PP_{0N}$  ( $R^2 = 0.09$  to 0.12), whereas the sum of precipitation ( $R^2 \leq 0.16$ ), AWDR ( $R^2 \leq 0.18$ ), maximum and mean precipitation ( $R^2 \leq 0.11$ ), and SDI variables ( $R^2 \leq 0.09$ ) had relationships with  $PMN_{an}$  from  $V5_{0N}$  and  $V5_{180N}$  (Table 4). The relationship between  $PMN_{an}$  and the

**Table 5. Pearson correlation coefficients of soil properties.**

Variable†	% Clay	% Silt	CEC	TC	TOC	SOM	TN	C/N	pH-salt	pH-water	BD-Measured	BD-Saxton
% Sand	-0.66*	-0.90*	-0.54*	-0.32*	-0.36*	-0.49*	-0.42*	0.06	0.11*	0.13*	0.54*	0.72*
% Clay	–	0.27*	0.91*	0.60*	0.63*	0.67*	0.62*	0.40*	0.27*	0.07	-0.61*	-0.75*
% Silt		–	0.17*	0.06	0.09	0.24*	0.18*	-0.31*	-0.27*	-0.21*	-0.34*	-0.49*
CEC			–	0.81*	0.84*	0.84*	0.81*	0.57*	0.34*	0.21*	-0.69*	-0.72*
TC				–	0.98*	0.93*	0.96*	0.60*	0.39*	0.32*	-0.71*	-0.64*
TOC					–	0.97*	0.98*	0.63*	0.32*	0.25*	-0.73*	-0.69*
SOM						–	0.97*	0.54*	0.18*	0.12	-0.74*	-0.76*
TN							–	0.49*	0.27*	0.21*	-0.74*	-0.71*
C/N								–	0.35*	0.25*	-0.39*	-0.35*
pH-salt									–	0.92*	-0.20*	-0.03
pH-water										–	-0.13	0.08
BD-measured											–	0.72*

\* Significant at the 0.05 probability level.

† BD, bulk density; CEC, cation exchange capacity; SOM, soil organic matter; TC, total C; TN, total N; TOC, total organic C.

sum of precipitation and AWDR was positive because greater uniformity in precipitation can stimulate N mineralization by consistently rewetting the soil (Kuz'yakov et al., 2000; Murphy et al., 1998; Wu et al., 2008). These results indicate that the quantity and evenness of precipitation are important for increasing N mineralization, but both variables were similarly related to  $PMN_{an}$ .

Temperature ( $R^2 \leq 0.20$ ) and precipitation ( $R^2 \leq 0.18$ ) variables overall had weaker relationships with  $PMN_{an}$  compared with soil properties ( $R^2 \leq 0.40$ ) (Table 4). These relationships agree with the findings from Dessureault-Rompré et al. (2010). Soil properties may be more important because they influence the size and quality of the organic N pool, which in turn affects the amount and rate of N mineralization (Gentile et al., 2011; Gil and Fick, 2001; Mazzilli et al., 2014; Sierra, 1992). Also, because soil properties are partially the result of long-term weather conditions (Cabrera et al., 2005; Franzluebbers et al., 2001; Kuz'yakov et al., 2000), soils may already integrate the effects of weather on  $PMN_{an}$ . The fact that soil properties have the best relationship with  $PMN_{an}$  is advantageous because these properties, unlike weather, are spatially and temporally more stable, providing consistency in potential mineralization estimates over years. Because  $PMN_{an}$  has been strongly related to microbial biomass and respiration (Doran, 1987; Franzluebbers et al., 2000; Myrold, 1987; Schomberg et al., 2009), it is possible that the remaining variability of  $PMN_{an}$  not explained by soil and weather conditions in our study may be explained by biological processes. However, because the focus of this study was to determine the relationship between soil and weather conditions and  $PMN_{an}$ , we can only speculate on the effect of microbial population on  $PMN_{an}$ .

### Anaerobic Potentially Mineralizable N Prediction

Mean  $R^2$  values for regression models using soil properties (including soil  $NO_3-N$  and  $NH_4-N$ ) and precipitation and temperature prior to soil sampling to predict  $PMN_{an}$  were 0.57 at  $PP_{0N}$ , 0.49 at  $V5_{0N}$ , and 0.50 at  $V5_{180N}$  when averaged across four variable selection methods (Stepwise, Forward, Backward, and Lowest CP; data not shown). These variable selection methods most often included one or more soil properties and at least one precipitation variable. The following variables were selected to predict  $PMN_{an} > 50\%$  of the time: percent sand, bulk density (measured and Saxton), total organic C, SOM, total N, cation exchange capacity, pH-water,  $NO_3-N$  from 0 to 30 cm, mean precipitation, SDI, AWDR, mean temperature, and GDD. Other studies also found strong relationships when selecting one or more of these variables to predict mineralizable N (Dessureault-Rompré et al., 2010, 2015; Hassink, 1994; Schomberg et al., 2009).

The stepwise variable selection method alone was used to determine the order in which variables were selected and how much  $PMN_{an}$  variability each soil and weather measurement explained. The first variable selected to predict any of the  $PMN_{an}$  values was either total N, bulk density-Saxton, total C, total organic C, or SOM (Table 6). The first variable selected through the stepwise selection method accounted for 57% of the total  $R^2$ , on average. All other variables selected and added to the mod-

el had a partial  $R^2 \leq 0.14$  when averaged across lengths within incubation length within each sample timing and N rate treatment. The soil property variables contributed the most to the total  $R^2$  (83% of  $R^2$ ), followed by precipitation (15% of  $R^2$ ) and temperature (4% of  $R^2$ ), when averaged across all treatments. Other researchers have observed similar findings where soil properties are the strongest predictors of potentially mineralizable N and where regression equations predicting mineralizable N normally include an estimate of SOM, soil texture, and climate (Dessureault-Rompré et al., 2010, 2015; Schomberg et al., 2009). Our results, as well as those cited here, show the strong influence soil properties have on  $PMN_{an}$ , with precipitation prior to soil sampling being a secondary influence and all temperature variables prior to soil sampling having a minor influence.

The variables within each of the soil properties, precipitation, and temperature categories were often strongly correlated (Tables 5; Supplemental Tables S1–S5). Collinearity tends to lead to the selection of typically only one variable from a group of strongly correlated variables during the selection process. When a selected variable was replaced with another variable with which it was strongly correlated ( $R > 0.60$ ), the  $R^2$  value for the model only decreased up to 0.15 and increased up to 0.01 for soil properties (including soil  $NO_3-N$  and  $NH_4-N$ ), decreased up to 0.12 for precipitation, and decreased up to 0.03 and increased up to 0.04 for temperature variables (data not shown). This result demonstrates that many variables can be used to obtain similar estimates of  $PMN_{an}$ . This can be advantageous in situations where existing databases have a limited number of variables to choose from. For example, total N or bulk density was the first variable selected by Stepwise to predict  $PMN_{an}$  66% of the time when averaged across all treatments, but farmers do not commonly test for these variables. However, SOM is routinely measured and can be used instead of total N or bulk density to predict  $PMN_{an}$  with similar accuracy. Understanding what commonly available soil and weather variables are useful to predict  $PMN_{an}$  may improve the utility of  $PMN_{an}$  as a tool to manage N fertilizer rates more effectively.

Predictability of  $PMN_{an}$  from  $PP_{0N}$  ( $R^2 = 0.54-0.69$ ) at each incubation length was greater than predicting  $PMN_{an}$  from either V5 N rate ( $R^2 = 0.43-0.59$ ) (Table 6). Increasing incubation time beyond 7 d improved  $R^2$  by an average of 8%, with a high of 16% coming from the V5 sample timing after N fertilizer was applied at planting ( $V5_{180N}$ ). The reduced predictability of  $PMN_{an}$  after N fertilizer addition with the 7-d incubation time demonstrates the difficulty of predicting N mineralization after N fertilization, which agrees with the findings of others (Fernández et al., 2017; Kuz'yakova et al., 2006; Ma et al., 1999). This reduced predictability may be because the quality of organic matter varied among experimental sites in this study (Table 2), and this interacts with the influence of N fertilizer on N mineralization (Chen et al., 2014; Jenkinson et al., 1985; Kuz'yakova et al., 2006).

Corn growers in the US Midwest region can currently modify their N fertilizer rate based on soil tests obtained before N fertilizer application. Our results indicate that using  $PMN_{an}$

from soil samples taken before N fertilization may reduce the effectiveness of  $PMN_{an}$  as an N management tool. However, using 14- or 28-d incubation periods may overcome this challenge because the predictability of  $PMN_{an}$  after fertilization ( $V5_{180N}$ ) from a 14- and 28-d incubation period using soil and weather conditions was more similar to  $PMN_{an}$  without N fertilization. The use of this longer incubation period might be important in obtaining better estimates of N fertilizer needs.

## CONCLUSIONS

Greater distribution of precipitation and warmer temperatures early in the season prior to sampling resulted in greater  $PMN_{an}$ , but, more importantly, soil properties directly or indirectly associated with greater SOM also increased  $PMN_{an}$ . The strength of the relationships between soil properties and  $PMN_{an}$  from  $PP_{0N}$ ,  $V5_{0N}$ , and  $V5_{180N}$  varied by  $\leq 10\%$ . Although for weather conditions before sampling, the delayed V5 samplings had more relationships compared with the preplant timing likely because weather conditions had more time to influence N min-

eralization. Furthermore, although weather is often considered an influential factor on  $PMN_{an}$ , we showed that soil properties (except for inorganic N) had better relationships with  $PMN_{an}$ . The fact that soil properties have the strongest relationship with  $PMN_{an}$  may be important in the development of N management tools because many soil properties are more stable from year to year than weather conditions.

The relationships between  $PMN_{an}$  and soil properties and weather conditions alone were slightly weak ( $R^2 \leq 0.40$ ) but greatly increased when soil and weather conditions were used together to predict  $PMN_{an}$  ( $R^2 \leq 0.69$ ). These results emphasize the need to better quantify soil properties and their interactive effect with precipitation and temperature to better understand their influence on mineralizable N and to potentially improve N management using  $PMN_{an}$ . Total N, bulk density-Saxton, total C, total organic C, or SOM was the first variable selected by the Stepwise selection process to predict  $PMN_{an}$  and provided the greatest contribution to  $R^2$ . Because SOM is routinely measured and can be used instead of these other measurements without

**Table 6. Partial  $R^2$  and total  $R^2$  values for the prediction of the anaerobic potentially mineralizable N soil test ( $PMN_{an}$ ) from soil samples obtained before planting and N fertilizer application ( $PP_{0N}$ ) and at the V5 development stage where zero ( $V5_{0N}$ ) or 180 kg N ha<sup>-1</sup> ( $V5_{180N}$ ) was applied at planting and incubated for 7, 14, and 28 d as a function of soil properties, precipitation, and temperature variables across 32 site-years selected by the Stepwise selection method. Bold numbers indicate the soil or weather condition that was selected first by the Stepwise selection method and contributed the most to the total explained variability.**

Variable†	PP <sub>0N</sub>			V5 <sub>0N</sub>			V5 <sub>180N</sub>		
	7 d	14 d	28 d	7 d	14 d	28 d	7 d	14 d	28 d
	Partial $R^2$								
Soil physical characteristics									
% Sand	0.04	0.08	0.05	–	–	–	–	–	–
% Clay	–	–	–	0.03	–	–	–	–	0.03
BD-Saxton	–	–	0.01	<b>0.20</b>	<b>0.24</b>	<b>0.35</b>	0.06	0.09	0.02
Soil chemical characteristics									
TC	–	–	–	–	–	–	<b>0.24</b>	–	–
TOC	–	–	0.05	–	–	–	0.04	0.02	<b>0.37</b>
SOM	–	–	–	–	–	0.01	0.03	<b>0.29</b>	–
TN	<b>0.33</b>	<b>0.30</b>	<b>0.40</b>	–	–	0.03	–	–	–
CEC	–	–	–	–	–	–	0.03	–	–
pH-salt	–	–	–	0.14	0.05	0.03	–	–	0.05
pH-water	0.04	0.02	0.02	–	–	–	–	–	–
Inorganic N‡									
NH <sub>4</sub> -N§ 0–30 cm	–	–	–	–	–	0.03	–	–	–
NO <sub>3</sub> -N§ 0–30 cm	0.03	–	–	–	–	–	0.05	0.03	–
NO <sub>3</sub> -N 0–90 cm	–	0.04	–	–	–	–	–	–	–
Precipitation§									
Max	–	0.01	0.02	–	–	–	–	–	–
Mean	–	–	–	–	–	–	0.07	0.04	–
SDI	0.08	0.12	0.07	0.07	–	–	0.03	0.04	–
AWDR	–	–	–	–	0.10	0.08	–	–	–
Temperature§									
Mean maximum	–	0.03	0.03	–	–	–	–	–	–
Mean minimum	–	–	–	–	–	–	–	0.05	–
Mean	–	–	–	–	–	–	–	–	0.05
GDD	–	–	–	–	–	–	0.01	–	0.02
	–Total $R^2$ –								
	0.54	0.57	0.69	0.52	0.57	0.56	0.43	0.59	0.51

† AWDR, abundant and well-distributed rainfall; BD, bulk density; CEC, cation exchange capacity; GDD, growing degree-day; SDI, Shannon diversity index; SOM, soil organic matter; TC, total C; TN, total N; TOC, total organic C.

‡ Ammonium and nitrate measured in treatment and at timing of  $PMN_{an}$  sampling.

§ Period used when regressing precipitation and temperature variables:  $PP_{0N}$ , 30-d before pre-plant sampling;  $V5_{0N}$  and  $V5_{180N}$ , pre-plant sampling to V5 corn development stage.



substantially affecting  $PMN_{an}$  predictability, this parameter may be the best suited for practical considerations. The predictability of  $PMN_{an}$  from 7-d incubations decreased when delaying soil sampling from preplant to V5 regardless of N fertilization but increased with longer incubations, with a greater increase coming when fertilized at planting ( $V5_{180N}$ ). This result is important because most producers fertilize their fields before the V5 development stage and indicates the potential of  $PMN_{an}$  from longer incubation periods being able to better estimate N mineralization when N fertilizer is applied. These results demonstrate that soil and weather conditions are important when predicting  $PMN_{an}$  ( $R^2 \leq 0.69$ ) and need to be considered in future research working to further improve  $PMN_{an}$  predictability and utility.

## SUPPLEMENTAL MATERIAL

The supplemental material includes five additional tables. These tables contain Pearson correlation coefficients of soil nitrate-N and ammonium-N measurements from different sample timings and N fertilizer rates. In addition, there are tables with Pearson correlation coefficients of precipitation and temperature variables from the time period of 30-d before pre-plant to pre-plant sample timing and from the pre-plant sample timing to the V5 corn development stage.”

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