11-1-2021

Soil hydrologic grouping guide which soil and weather properties best estimate corn nitrogen need

Gregory Mac Bean
McCain Foods

Curtis J. Ransom
United States Department of Agriculture, curtisransom@gmail.com

Newell R. Kitchen
United States Department of Agriculture

Peter C. Scharf
University of Missouri

Kristen S. Veum
United States Department of Agriculture

See next page for additional authors

Authors
Gregory Mac Bean, Curtis J. Ransom, Newell R. Kitchen, Peter C. Scharf, Kristen S. Veum, James J. Camberato, Richard B. Ferguson, Fabián G. Fernández, David W. Franzen, Carrie A.M. Laboski, Emerson D. Nafziger, John E. Sawyer, and Robert L. Nielsen

Received: 24 March 2021 | Accepted: 7 September 2021 | Published online: 27 October 2021

DOI: 10.1002/agj2.20888

Agronomy Journal

ARTICLE

Soil Fertility and Crop Nutrition

Soil hydrologic grouping guide which soil and weather properties best estimate corn nitrogen need

Gregory Mac Bean[1] | Curtis J. Ransom[2] | Newell R. Kitchen[2] | Peter C. Scharf[3] | Kristen S. Veum[2] | James J. Camberato[4] | Richard B. Ferguson[5] | Fabián G. Fernández[6] | David W. Franzen[7] | Carrie A. M. Laboski[8] | Emerson D. Nafziger[9] | John E. Sawyer[10] | Robert L. Nielsen[4]

[1] McCain Foods, Oakbrook Terrace, IL 60181, USA

[2] USDA-ARS Cropping System and Water Quality Res. Unit, Columbia, MO 65211, USA

[3] Dep. of Plant Science, Univ. of Missouri, Columbia, MO 65211, USA

[4] Dep. of Agronomy, Purdue Univ., West Lafayette, IN 47907, USA

[5] Dep. of Agronomy and Horticulture, Univ. of Nebraska-Lincoln, Lincoln, NE 68583, USA

[6] Dep. of Soil, Water, and Climate, Univ. of Minnesota, St. Paul, MN 55108, USA

[7] Dep. of Soil Science, North Dakota State Univ., Fargo, ND 58105, USA

[8] Dep. of Soil Science, Univ. of Wisconsin-Madison, Madison, WI 53706, USA

[9] Dep. of Crop Sciences, Univ. of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

[10] Dep. of Agronomy, Iowa State Univ., Ames, IA 50011, USA

Correspondence
Curtis Ransom, USDA-ARS Cropping System and Water Quality Res. Unit, Columbia, MO, USA.
Email: curtisransom@gmail.com

Assigned to Associate Editor Ram Ray.

Funding information
Corteva Agriscience

Abstract

Nitrogen fertilizer recommendations in corn (Zea *mays* L.) that match the economically optimal nitrogen fertilizer rate (EONR) are imperative for profitability and minimizing environmental degradation. However, the amount of soil N available for the crop depends on soil and weather factors, making it difficult to know the EONR from year-to-year and from field-to-field. Our objective was to explore, within the framework of hydrologic soil groups and drainage classifications (HGDC), which site-specific soil and weather properties best estimated corn N needs (i.e., EONR) for two application timings (at-planting and side-dress). Included in this investigation was a validation step using an independent dataset. Forty-nine N response trials conducted across the U.S. Midwest Corn Belt over three growing seasons (2014–2016) were used for recommendation model development, and 181 independent site-years were used for validation. For HGDC models, soil organic matter (SOM), clay content, and evenness of rainfall distribution before side-dress N application were the properties generally most helpful in predicting EONR. Using the validation data, model

Abbreviations: EONR, economically optimal nitrogen rate; HGDC, hydrologic soil group and drainage class; K_{sat}, saturated hydraulic conductivity; MRTN, maximum return to nitrogen; PAWC, plant-available water content; PD, poorly drained; SDI, Shannon Diversity Index; SOM, soil organic matter; SSURGO, Soil Survey Geographical Database; WD, well drained ; SRGO_PAWC, SSURGO plant-available water content.

recommendations were within 34 kg N ha^{-1} of EONR for 37 and 42% of the sites with a root mean square error (RMSE) of 70 and 68 kg N ha^{-1} for at-planting and side-dress applications, respectively. Compared to state-specific recommendations, sites needing <100 kg N ha^{-1} or no N were better estimated with HGDC models. In contrast, for sites where EONR was >150 kg N ha^{-1}, HGDC models underestimated N needs compared to state specific. These results show HGDC groupings could aid in developing tools for N fertilizer recommendations.

1 | INTRODUCTION

Sustainable N fertilizer practices in corn (*Zea mays* L.) are accomplished by applying the correct amount of N fertilizer and at the correct time necessary to reach the economically optimal nitrogen rate (EONR). These practices help maintain profit while minimizing N loss to the environment. Commonly, N fertilizer is overapplied to ensure maximum yield, resulting in poor N use efficiency and environmental pollution (Schröder et al., 2000; Shanahan et al., 2008; Tremblay et al., 2012). Due to the spatial and temporal variability of soil and weather factors impacting the fate of soil N and corn N uptake being negligible early in the growing season, determining EONR before or early in the growing season is difficult. For these reasons, split-applications with some fertilizer applied in-season have merit.

Historically, N fertilizer recommendations have been derived from expected grain yield (Blackmer et al., 1992; Gehl et al., 2005), but this strategy failed to consider N response to soil and weather conditions for the upcoming year. Soil and weather metrics have been related to corn N response (Tremblay et al., 2012; Xie et al., 2013). Corn N response, as measured by the yield increase with N fertilization, is significantly related to EONR ($r^2 = .52$; Meisinger et al., 2008). Understanding weather and soil factors and their relationship to crop response can improve N fertilizer recommendations and help prevent environmental losses of N (Morris et al., 2018).

Soil texture and organic matter (among other variables) impact soil water flow, available N (organic matter mineralization), plant-available water content (PAWC), the transportation and availability of ions (Schaetzl & Anderson, 2014), and crop yield (Armstrong et al., 2009; Tremblay et al., 2012; Zhu et al., 2009). Spatial diversity of these properties across a landscape combined with variable total rainfall, the evenness of rainfall over the growing season, and temperature contribute to the complexity of N use in crops and its fate in the environment (Tremblay et al., 2012). Denitrification most often occurs in fine-textured soils experiencing anaerobic conditions from excessive rainfall and warm soil temperatures (Blevins et al., 1996). In contrast, NO_3^- leaching below the rooting depth results when large amounts of rainfall occur on soils with low water-holding capacity or on coarse-texture soils (Power et al., 2001). Volatilization may also occur if certain N fertilizers, such as urea, are not incorporated into the soil (Ma et al., 2010). These interactions require different methods of N management.

Precipitation and temperature generally drive plant growth and influence soil conditions, including soil microbial activity (Tremblay & Bélec, 2006), which ultimately influence corn yield. In years with above-average rainfall, corn has generally been found to require more N fertilizer than years of below-average rainfall (Yamoah et al., 1998). Across North America, corn yield response to N fertilization was affected the most by precipitation during June and July, and by temperatures during July and August (Jeutong et al., 2000). The distribution or evenness of rainfall has also been found significant in explaining corn responsiveness to N fertilizer and subsequently, crop yield (Reeves et al., 1993; Shaw, 1964; Tremblay et al., 2012). Locations with large amounts of soil moisture early in the growing season promoted N loss through denitrification and leaching, and increased the grain yield responsiveness to N fertilizer (Tremblay et al., 2012). Rainfall and temperature are widely accepted weather attributes directly affecting soil factors such as oxygen levels, soil microbial activity, and decomposition of organic matter (e.g., N and S mineralization), which affects nutrient availability, plant-available water, and ultimately crop yield (Dellinger et al., 2008; Kyveryga et al., 2007; Power et al., 2001; Tremblay, 2004; Tremblay & Bélec, 2006; Tremblay et al., 2012). Research is needed to determine how soil and weather factors can improve N fertilizer recommendations.

Some of the above-mentioned soil and weather properties interact (e.g., clay percentage and excessive precipitation) to affect plant growth, and elements of these interactions have been used by the USDA-NRCS to classify soils. Each USDA-NRCS Soil Survey Geographical Database (SSURGO) soil series is assigned both a hydrologic soil group and a drainage classification (USDA NRCS, 2009). Hydrologic soil groups are based on the depth to a restrictive layer or water table, the transmission rate of water through the soil profile, soil texture, soil structure, and the degree of soil swelling when saturated.

The seven drainage classifications are centered on the frequency and duration of wet periods, the occurrence of internal free water, and the rate of water removal from the soil profile. When considering N loss on a watershed scale, hydrologic groups were one of the most important factors in estimating N movement and loss pathways (Blanchard & Lerch, 2000). In forested soils in southern Quebec, drainage class was significantly related to N transformation rates and internal N cycling (Ullah & Moore, 2009).

Many publicly available N fertilizer rate recommendation tools have been developed and tested (Morris et al., 2018). However, many of these tools do not consistently relate well to EONR, highlighting the need for additional improvement (Puntel et al., 2018; Ransom et al., 2020; Sela et al., 2018; Setiyono et al., 2011; Thompson et al., 2015). Only a few recommendation tools have used soil hydrologic groupings or drainage classes, yet expanding its use could improve estimation of corn N fertilizer needs. This was observed with the Illinois soil N test, as its accuracy improved when drainage classification was taken into account (J. Williams et al., 2007). Our objective was to explore, within the framework of hydrological soil groupings and drainage classifications, which site-specific soil and weather properties best estimate corn N needs, with the goal being to improve corn N recommendations. Included in this investigation was a validation step using an independent dataset.

Core Ideas

- Soil hydrologic classifications aid in determining corn N fertilizer rates.
- Economically optimal N rate was best predicted by different soil and weather properties for each hydrologic group.
- Soil organic matter, clay, and rainfall evenness generally helped in estimating economically optimal N rate.
- Compared to state N recommendations, developed models were better when economically optimal N rate <100 kg ha^{-1}.

2 | MATERIALS AND METHODS

2.1 | Research for model development

This research for developing the models was conducted as part of a public–private collaboration between eight major land-grant universities (Iowa State University, University of Illinois, Purdue University, University of Minnesota, University of Missouri, North Dakota State University, University of Nebraska, and the University of Wisconsin) within the U.S. Corn Belt and Corteva Agriscience (Kitchen et al., 2017). Yield and soil measurements from these plot studies provided the measurements needed to generate N fertilizer recommendation models and N response functions.

Forty-nine corn N response trials were conducted during 2014–2016 in eight midwestern Corn Belt states. In each state, two sites varying in productivity were selected for each growing season, resulting in six sites per state (Missouri had three in 2016). The majority of sites were corn after soybean [*Glycine max* (L.) Merr.]. Productivity was determined by historical yield and general soil productivity. Research sites were planted at a target population of 86,450 plants ha^{-1} using Pioneer brand hybrids (Corteva Agriscience) adapted for the selected sites within the region. Descriptions of management for all sites are presented in Kitchen et al. (2017) and Bean et al. (2018a).

Fourteen different N application treatments replicated four times were used in a randomized complete block design. Nitrogen treatments comprised of dry-prilled NH_4NO_3 fertilizer broadcast applied. The "at-planting" fertilizer was applied within 48 h of initial planting, while the side-dress fertilizer was applied between the V8 and V10 leaf stage (Abendroth et al., 2011). At-planting rates ranged from 0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments. Side-dress rates ranged from 0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments, but treatments were split applied with 45 kg N ha^{-1} at planting and the remaining N at the V9 development stage. Additional details about the trial sites, treatments, and measurement have been previously documented (Kitchen et al., 2017). An EONR [corn grain price, US$0.158 kg^{-1} ($4.00 bu^{-1}), N fertilizer cost, $0.88 kg N^{-1} ($0.40 lb^{-1})] was calculated for both the at-planting and split N treatments. The quadratic-plateau function was found most appropriate for all but one site where a quadratic function was a better fit (Kitchen et al., 2017). The EONR values were calculated as:

$$\text{EONR} = \frac{-b - (\text{N:corn price})}{(2c)} \tag{1}$$

where b and c were the linear and quadratic response coefficients from the optimized quadratic-plateau function. For evaluating HGDC-based N recommendation models for corn that received 45 kg N ha^{-1} at planting, the EONR value was reduced by this same amount so that it represents the N fertilizer that was applied as side-dress. Throughout the rest of this analysis "EONR" is used in the general sense to represent both application timings.

TABLE 1 A list and brief description of the outside datasets used in the validation analysis

State	Study characteristics	Site-years	References
IA	Long-term corn N response plot studies established (1999–2016) at several Iowa State University Research Farms to observe the effect of N fertilization on soil organic C, crop yield in varying corn cropping systems, and corn model development	68	Brown et al., 2014; Puntel et al., 2016; Poffenbarger et al., 2017
IN	Large plot N response studies at several Purdue University Agricultural Centers focused on fertilizer application timing, rate and residual effects, and canopy reflectance	67	Emmert, 2009; Miller, 2012; Moser, 2016; J. J. Camberato, personal communication, March 2018
MO	Field-length N response sites used in the comparison between variable-rate canopy sensor-based N fertilizer recommendations and producer N rate. Additional studies on corn N response related to soil texture and weather properties	5	Kitchen et al., 2010; Tremblay et al., 2012
NE	Large plot N response studies aimed at incorporating management zones and canopy sensing ultimately to improve N recommendation equations	14	Crowther, 2018
ND	Nitrogen response studies used to compare satellite imagery and canopy reflectance sensors as yield predictors in corn. Additional studies on using rainfall data to improve canopy sensor-based yield predictions	11	Bu et al., 2017; Sharma et al., 2018
WI	Evaluating cover crops and nitrapyrin for improved manure N availability	16	Teeter, 2019; C. A. M. Laboski, personal communication, March 2018

2.2 | Research for model validation

Data used to validate the models were collected from six major land-grant universities (Iowa State University, Purdue University, University of Missouri, North Dakota State University, University of Nebraska, and the University of Wisconsin) within the U.S. Corn Belt. These corn N fertilizer response studies were separate from those used to generate the models and represented a wide range of soil and weather conditions. Of the 181 total, 165 site-years (59 at-planting and 106 side-dress) were relevant to the models being developed and could be used for validation. These included sites that were conducted from 1999 to 2017. A brief description of the collected datasets is presented in Table 1 and additional baseline information supplied in supplemental tables. An EONR for each site and N application timing was calculated using the same corn grain price to N fertilizer cost ratio mentioned above.

2.3 | Measurements considered for model development

Soil sampling at each site was conducted in the spring before planting. Bulk soil apparent electrical conductivity surveys using a Veris 3100 (Veris Technologies) guided site characterization soil sampling. For soil characterization, two adjacent 1.2-m deep soil cores (i.d. 4.76 cm) were obtained from each of the four replications at each site using a Giddings Model no. 5-UV/MGSRPSUV (Giddings Machine Company). One core was used to measure bulk density and soil moisture at sampling while the other was processed for physical and chemical analyzes, including: particle size (pipette method), cation exchange capacity, total C, total organic C, total inorganic C, soil organic matter (SOM), and pH (salt and water) following standardized procedures (Nelson & Sommers, 1996; Soil Survey Staff, 2014). Plant available water content (PAWC) was calculated as the difference between the soil water content at field capacity and permanent wilting point using procedures outlined by Saxton and Rawls (2006). Results were average across all replicated cores to represent the site. Soil biological activity was assessed from samples taken at the V5 corn growth stage using the Cornell Soil Health Assessment CASH soil respiration test (Moebius-Clune et al., 2016), a test measuring CO_2 output during a 4-d incubation period (Zibilske, 1994).

The SSURGO data for model development were obtained from the USDA-NRCS via the "Web Soil Survey" website and the "Soil Data Viewer" plug-in available in ArcMap (Esri) or the Soil Web (O'Geen et al., 2017). If more than one SSURGO mapping unit was assigned to the research site, the most dominant SSURGO mapping unit was chosen. Data collected from SSURGO included PAWC, clay, and SOM.

Weather data were collected using a HOBO U30 Automatic Weather Station (Onset Computer Corporation). Daily

TABLE 2 Weather parameters calculations from the time of planting to the time of side-dress using formulas and descriptions outlined in Table 2 of Tremblay et al. (2012)

Weather parameter	Calculation
Growing degree days	Growing degree days = $\sum(T_{min} + T_{max})/2 - 10$ ˚C where T_{min} and T_{max} are the minimum and maximum daily temperatures; if $T_{max} > 30$˚C, $T_{max} = 30$ ˚C.
Total precipitation	Total precipitation = $\sum$(Rain), where Rain is the daily rainfall and irrigation amounts (mm).
Shannon Diversity Index (SDI)	SDI = $[-\sum \text{pi} \times \ln(\text{pi})]/\ln(n)$, where pi = Rain/total precipitation and n = number of days in the period. SDI = 1 implies complete evenness of rainfall and SDI = 0 implies complete unevenness.
Abundant and well-distributed rainfall	SDI × total precipitation.

temperatures were used to calculate growing degree days while daily precipitation (and irrigation) was used to calculate the total precipitation, Shannon Diversity Index (SDI), and abundant and well-distributed rainfall (Table 2). The SDI measures the evenness of precipitation by calculating the proportion of daily precipitation to the total cumulative precipitation during a specified time period. For additional details about the calculations and interpretation for these metrics used in reference to N management, refer to Tremblay et al. (2012) and Bean et al. (2018b).

2.4 | Measurements collected for model validation

For many validation sites, soil information was supplied by the principal investigators of the experiments or additional analyzes were performed on stored soil (Table 1). For site-years with missing soil information or samples, additional soil sampling was performed in the fall of 2018. Sites requiring additional soil collection were sampled in a "Z" pattern across the footprint of the site location via a Backsaver hand soil probe (JMC Soil Samplers) with no <10 sampling points per site. Samples were taken and aggregated in 0-to-30- and 30-to-60-cm depth increments and analyzed using the same methods described above at the University of Missouri Soil Health Assessment Center or the USDA-ARS Soil Quality Lab (Columbia, MO). The SSURGO data were obtained the same way as described for sites under model development.

Weather data were collected either from on-site weather stations or the National Oceanic and Atmospheric Administration's (NOAA) cooperative climate dataset resource (http://www.ncdc.noaa.gov). Weather data gathered through NOAA were taken from the weather station nearest the site location. These were used to calculate the same weather metrics as described above under model development.

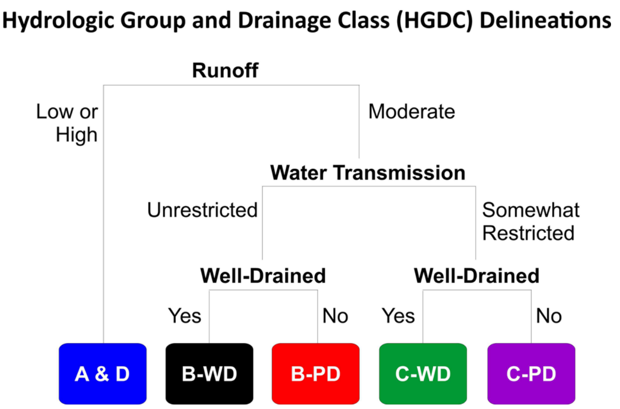

FIGURE 1 A schematic for delineating soils in order to develop site-specific N management recommendations. Soils were delineated using two United States Department of Agriculture–Natural Resources Conservation Service (USDA-NRCS) soil classification systems: (1) hydrologic soil groups (A, B, C, and D), and (2) drainage classes (well drained [WD] or poorly drained [PD])

2.5 | Site delineation by hydrologic soil group and drainage class

For both model development and validation sites, hydrologic groupings and soil drainage classifications were gathered from the SSURGO database via Soil Web (University of California). There are four USDA-NRCS hydrologic soil groups (A, B, C, D) with group A having the least potential for runoff and group D having the highest potential (Table 3). There are seven USDA-NRCS drainage classifications (excessively drained, somewhat excessively drained, well drained, moderately well drained, somewhat poorly drained, poorly drained, and very poorly drained), but for this analysis sites were grouped to be considered either poorly drained (PD) or well drained (WD). Initial site delineation was made by combining sites within hydrologic soil groups A and D, with no distinction of drainage class (Figure 1). Hydrologic soil group A and D were grouped together because they both have

TABLE 3 Hydrologic soil groups as defined by the USDA. The hydrologic soil group delineations are made with the considerations that (1) the intake and transmission of water are under the conditions of maximum yearly wetness, (2) the soil is not frozen, (3) the soil surface is bare, and (4) maximum swelling of expansive clays are measured (where applicable). It should also be noted that the soil surface slope is not considered and when assigning a soil to a hydrologic soil group, the least transmissive layer is used

Hydrologic group	Runoff potential	Water transmission	Soil texture	K_{SAT}	Depth to water table	Depth to impermeable layer
				cm h^{-1}	cm	
A	Low	Unrestricted	>90% sand and <10% clay	>14.5	>61	>51
B	Moderate low	Unrestricted	10–20% clay and 50–90% sand	3.6–14.5	>61	>51
C	Moderate high	Somewhat restricted	20–40% clay and <50% sand	0.36–3.6	>61	>51
D	High	Very restricted	>40% clay and <50% sand	<0.36	<61	<51

TABLE 4 Overview of soil and weather measurements considered in linear regression models for predicting economic optimal nitrogen rate (EONR). This linear regression analysis was performed within each USDA-NRCS defined hydrologic soil groups and drainage classifications for at-planting and side-dress N application timings. All soil information (measured and Soil Survey Geographical Database [SSURGO]) were tested using values from 0-to-30- and 0-to-60-cm depths. Weather variables were used only for side-dress treatments and calculated from time of planting to time of side-dress (V8–V10 stage)

Type	Factors evaluated
Weather	SDI, growing degree days, total precipitation, abundant and well distributed rainfall
Measured soil information	Clay, PAWC, SOM, organic C, total C, pH, soil respiration
SSURGO based information	Clay, SRGO_PAWC, SOM

Note. SDI, Shannon Diversity Index; PAWC, plant available water content (%); SRGO_PAWC, SSURGO plant available water (%); SOM, soil organic matter (%).

a high propensity for N loss–group A soils via leaching and group D soils via denitrification. For sites classified in soil groups B and C, further delineation was accomplished using the drainage class with soils being PD or WD, as shown in Figure 1. Thus, site delineation resulted in five groups and was the framework for model development of this investigation. For convenience, the five distinct groups will be referred to as HGDC A and D, HGDC B-WD, HGDC B-PD, HGDC C-WD, and HGDC C-PD.

2.6 | Statistics for model development and validation

Data were analyzed using SAS version 9.2 (SAS Institute Inc.) by delineated HGDC. The proc REG linear regression function was used for evaluating EONR (both N fertilizer timings) as a function of soil properties (both depth intervals of 0–30 and 0–60 cm) and weather variables (Table 4). Included were all two-way interactions between these variables. All at-planting models excluded measurements that were collected after planting (i.e., weather and soil respiration tests). Regression model outcomes producing the greatest probability significance (either single or two-way interaction variable) were used to generate N recommendation models within each HGDC delineation. Assessment of all HGDC N recommendation models was based on the RMSE of the difference between N recommendation and EONR, and by the percentage of sites within 34 kg N ha^{-1} of EONR. This value represents the amount of uncertainty around the EONR calculations and was based on 95% confidence intervals and profitable margins of \$2.50 ha^{-1}. The value of 34 kg N ha^{-1} is similar to what others have used for testing the performance of N recommendation tools (Laboski et al., 2014; Sawyer, 2013), and is similar to an economic-environmental threshold value identified with this same dataset (Bandura, 2017).

The HGDC N recommendations were validated using the same performance metrics described previously (i.e., RMSE and the percentage of sites within 34 kg N ha^{-1}). Additionally, this validation dataset was used to compare the HGDC N recommendations to the state-specific N recommendations. For Iowa, Indiana, North Dakota, and Wisconsin the Maximum Return to Nitrogen (MRTN) tool was used while for Missouri and Nebraska a state-specific yield goal approach was used. The MRTN values are derived for specific geographies (state, substate, or region) using many N yield response trials across multiple years (Nafziger et al., 2004; J. Sawyer et al., 2006). The Nebraska yield goal is calculated using expected

TABLE 5 Soil and weather variables related ($p < .05$) to the economic optimum nitrogen rate (EONR) as delineated by USDA-NRCS defined hydrologic soil groups and drainage class (HGDC). Results shown are for both N timings (at-planting and side-dress). Weather variables were used only for side-dress treatments and calculated from time of planting to time of side-dress (V9 ±1 stage)

N timing	HGDC Delineation	Variable	Model	r^2	*p* value
At-planting	A and D	–		–	–
	B-WD	SOM_{30}	$y = 251 – 44 – SOM_{30}$	0.64	.001
	B-PD	$PAWC_{30} \times SOM_{60}$	$y = 83 + 340 \times (PAWC_{30} \times SOM_{60})$	0.74	.039
	C-WD	$Clay_{30} \times SOM_{30}$	$y = -296 + 447 \times (Clay_{30} \times SOM_{30})$	0.78	.012
	C-PD	Total C_{30}	$y = 260 – 75 \times$ Total $carbon_{30}$	0.32	.016
Side-dress	A and D	SDI	$y = 265 + 645 \times SDI$	0.54	.015
	B-WD	Soil respiration[a]	$y = 193 – 0.6 \times$ Soil respiration	0.55	.003
	B-PD	SDI × $Clay_{60}$	$y = 11 + 929 \times (SDI \times Clay_{60})$	0.85	.017
	C-WD	SDI × $Clay_{30}$	$y = -191 + 1324 \times (SDI \times Clay_{30})$	0.70	.023
	C-PD	SDI × $SRGO\_PAWC_{60}$	$y = -171 + 100 \times (SDI \times SRGO\_PAWC_{60})$	0.48	.003

Note. SOM_{30} , soil organic matter in the upper 30 cm of soil; $PAWC_{30}$, plant available water content in the upper 30 cm of soil (%); SOM_{60}, soil organic matter in the upper 60 cm of soil; $Clay_{30}$, percentage clay in the upper 30 cm of soil; Total C_{30}, percentage carbon in the first 30 cm of soil; SDI, Shannon Diversity Index calculated from the time of planting to the time of N side-dress; $Clay_{60}$, percentage clay in the upper 60 cm of soil; $SRGO\_PAWC_{60}$, SSURGO gathered plant available water content in the upper 60 cm of soil (%).

[a]Soil respiration in the first 30 cm of soil as measured using the 4-d Cornell Soil Health Assessment test.

yield, estimated soil nitrate and N supplied from SOM, N supplied from irrigation, with an N credit applied for any previous year's soybean crop (Shapiro et al., 2008). The recommendation can then be adjusted based on soil texture and application timing. Similarly, the Missouri yield goal approach uses an expected yield and N supplied from the soil based on SOM and cation exchange capacity. A credit is also given for any previous grown soybean (Buchholz et al., 2004).

3 | RESULTS AND DISCUSSION

3.1 | Model development

The number of sites per HGDC were 9, 14, 5, 6, and 15 for HGDC A and D, B-WD, B-PD, C-WD, and C-PD, respectively. Soil and weather factors most significantly related to EONR for both N application timings are listed in Table 5.

3.1.1 | Fertilization at planting

For the at-planting N application time, no variables were found related to EONR for HGDC A and D. This is likely due to the uncertainty of predicting seasonal N need at the time of planting for these two contrasting soils, which have different N loss responses to weather events. Since "in season" weather information was not yet available, understanding corn N response within this HGDC was ineffective. Soil factors improved estimation of EONR of the other four HGDC groups (Table 5). For HGDC B-WD sites, EONR decreased as SOM increased in the first 30 cm of soil (Figure 2). This result suggests sites with greater amounts of SOM provided greater soil N, which led to reduced N fertilizer for EONR. With greater SOM, other properties also improve, including soil aggregation, which promotes infiltration, aeration, and root growth and development (Boyle et al., 1989). These properties help buffer against extreme weather conditions by storing soil water (A. Williams et al., 2016), which in turn allows for sustained biological activity and therefore conditions for N mineralization. A similar yet weaker response was found with HGDC C-PD but using total C (Figure 2). Since total C for these soils is the major portion of SOM, they are highly related. This property is also typically related to soil bulk density, a property important for promoting root growth (Hallmark & Barber, 1981). As total C increased, bulk density decreased. Although considered poorly drained, sites in HGDC C-PD with lower bulk densities (1.1–1.3 g cm^{-3}) and higher total C content were potentially less susceptible to N loss and/or greater N mineralization due to greater soil aeration. Interestingly, soils within this group had the largest range in EONR (>150 kg N ha^{-1}), suggesting these soils needed tools with greater flexibility when making N fertilizer recommendation.

With HGDCs B-PD and C-WD, it showed that EONR increased with increasing soil values (Figure 2). For HGDC B-PD the relationship was with the interaction between PAWC and SOM (60 cm) and for HGDC C-WD the relationship was with the interaction between clay and SOM (30 cm). As values of these interactions increase, we would expect drainage to decrease. An explanation of this outcome is that since these soils are poorly drained (HGDC B-PD) or have low saturated hydraulic conductivity (K_{SAT}; HGDC C-WD), they potentially experience anaerobic conditions during

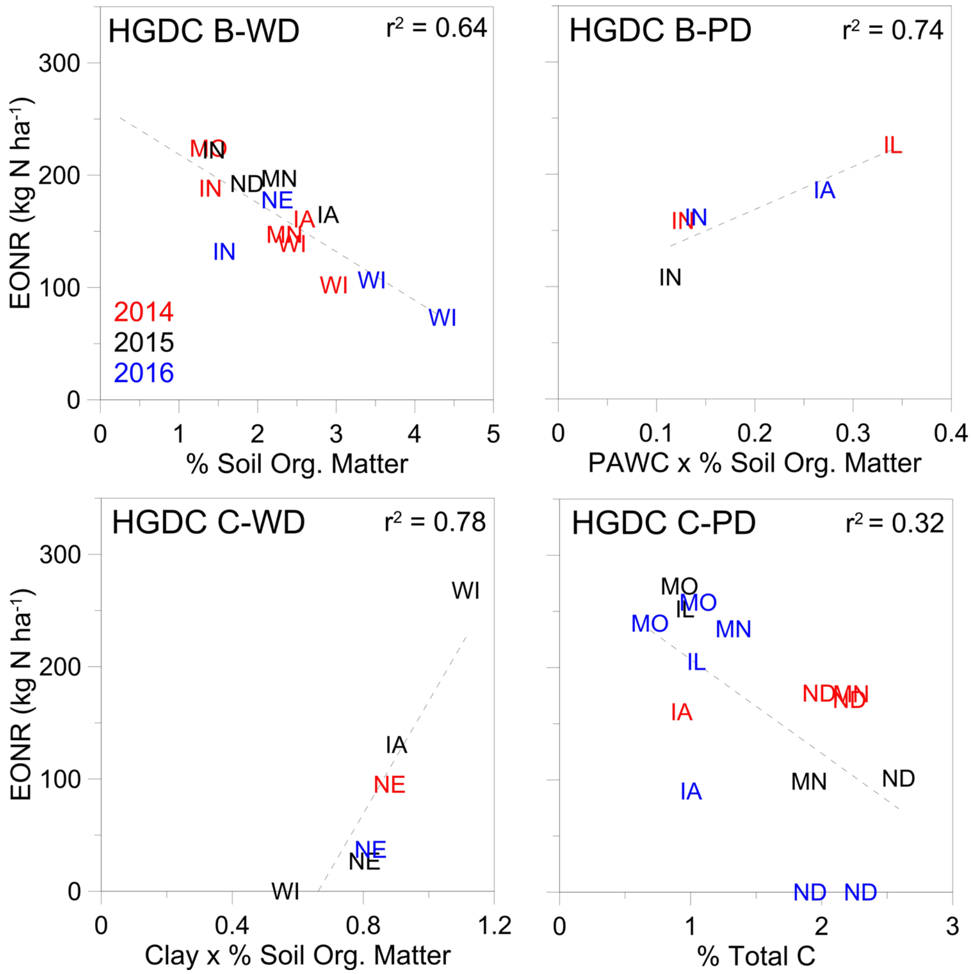

FIGURE 2 Economic optimal nitrogen rate (EONR) related to soil properties for at-planting N application within delineated hydrologic soil group and drainage class (HGDC; Figure 1). No properties were found significant for HGDC A and D. See Table 5 for details of equations. Values are represented by U.S. state abbreviations

portions of the growing season. When rainfall is excessive for these soils, anaerobic conditions persist and substantial inorganic N loss through denitrification may occur, and therefore high rates of fertilizer N are needed to reach EONR (Blevins et al., 1996).

3.1.2 | Fertilization at side-dress

For HGDC A and D, soil properties were not found to be as helpful in explaining variation in EONR, but EONR did increase with increasing rainfall evenness (Figure 3). Distribution of precipitation can be just as important as total precipitation, and can influence N uptake, mineralization, leaching, and denitrification (Tremblay et al., 2012). Hydrologic soil group A contains coarse-textured soils (>90% sand) with high K_{SAT} rates and a low runoff potential. Hydrologic soil group D contains soils that are high in clay content (>40%) with low K_{SAT} rates and a high runoff potential. Therefore, more evenly distributed precipitation events (higher SDI values) from the time of planting to side-dress allowed these soils to stay wet longer, which is conducive to N loss. Others comparing SDI to N response have found similar results (Kablan et al., 2017; Tremblay et al., 2012). It should be noted that temperature (e.g., growing degree days) was not found related to EONR. This is similar to other analyzes performed with this dataset and suggests precipitation is more helpful in understanding corn N response on a regional basis. These findings demonstrate that within HGDC A and D, the relationship between SDI and EONR can help in determining an in-season N fertilizer recommendation.

For HGDC B-WD, EONR decreased as soil respiration increased (Figure 3). This negative relationship was similar to that reported by Yost et al. (2018). As soil respiration increased, presumably the amount of plant-available N being supplied by soil became more abundant via increased microbial activity (i.e., mineralization), resulting in less need for inorganic N fertilizer to reach EONR. Not surprisingly, the coarse-textured Indiana sites with little organic matter (0.8 and 1.4%, respectively) and lower PAWC had the

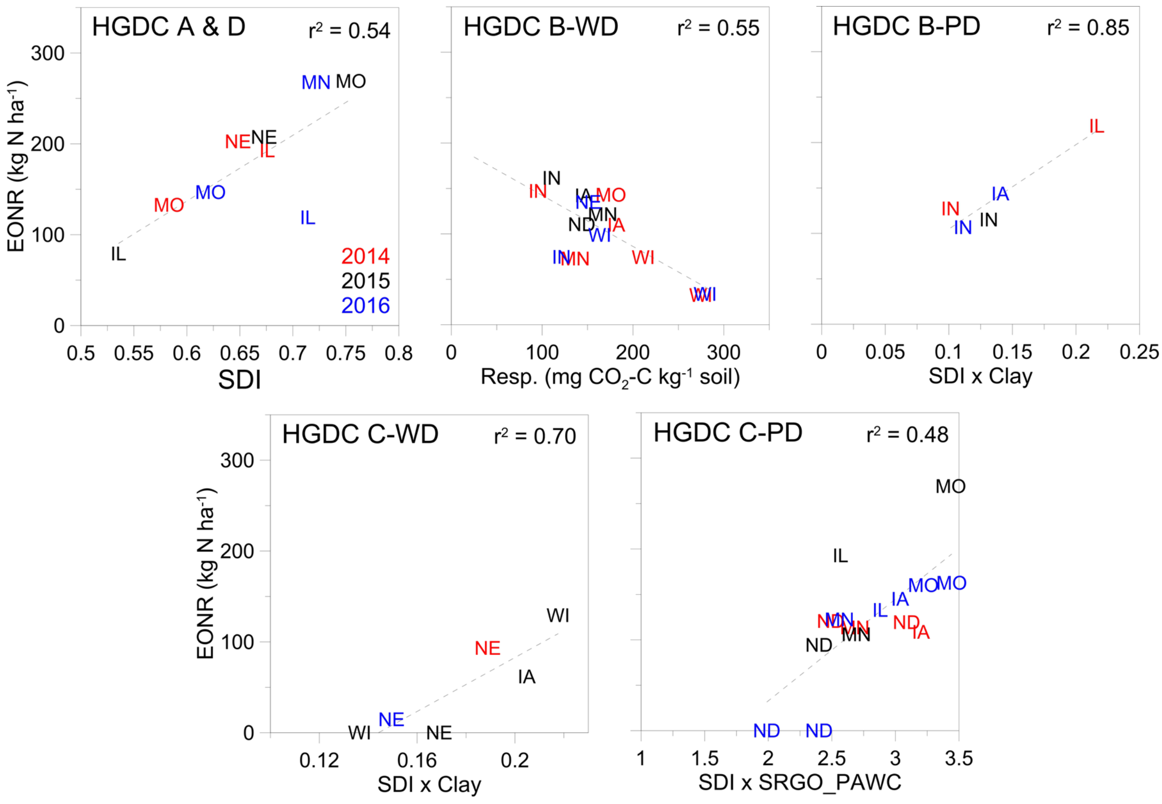

FIGURE 3 Economic optimal nitrogen rate (EONR) related to soil properties for side-dress N application within delineated hydrologic soil group and drainage class (HGDC; Figure 1). See Table 5 for details of equations. Values are represented by U.S. state abbreviations

lowest soil respiration and therefore the highest amount of inorganic N fertilizer required to reach EONR. In contrast, two of the Wisconsin sites (classified as either loam or silt loam) with greater amounts of organic matter (3.5 and 4.4%, respectively) and PAWC had the highest soil respiration and therefore the lowest amount of inorganic N fertilizer required to reach EONR. Soil microbial activity largely depends on soil temperature and moisture (Davidson & Janssens, 2006; Howard & Howard, 1993; Linn & Doran, 1984). Further, nitrifying bacteria are aerobic, requiring oxygen to make NO_2^- and NO_3^- and are therefore favored in well- drained soils (Goreau et al., 1980). Soils within HGDC B-WD seem to have been buffered against extreme temperature and moisture events, lessening the likelihood of leaching and denitrification, ultimately creating a suitable environment for microbial activity. Therefore, the sites in this group were less subject to year-to-year variations due to weather, allowing lab-derived soil respiration measurements to relate to EONR.

For both HGDCs B-PD and C-WD, EONR increased with the interaction between SDI and clay (Figure 3). Relative to HGDC B-WD sites, these sites were characterized by either poor drainage (i.e., wet at shallow depths during much of the growing season), a shallow water table, or greater clay content. As such, distribution of early season rainfall mattered. When precipitation distribution was high (i.e., high SDI), anoxic conditions in the root zone likely resulted, with denitrification following. These findings are similar to those found elsewhere (Tremblay et al., 2012). In other work, soil N supply was found to be greater on soils with relatively lower clay content (Shahandeh et al., 2011).

For HGDC C-PD, EONR was similarly related to SDI, but as an interaction with PAWC (Figure 3). A primary determinant of PAWC is soil texture, so not surprisingly the relationship for HGDC C-PD looks a lot like B-PD and C-WD. The HGDC C-PD sites had a great amount of clay and a low saturated hydraulic conductivity (K_{SAT}) (0.36–3.6 cm h^{-1}), which likely indicates a restrictive layer or shallow water table and with substantial or evenly distributed precipitation events caused periods of standing water during the growing season. It is possible that during years of sufficient but evenly distributed rainfall, these site characteristics resulted in higher fertilizer N need for optimal yield. Sites that were unique to the SDI x PAWC relationship typically had a reasonable explanation. For example, the high EONR seen with 2015 Missouri site was next to the Missouri River and had a near-surface elevated water table because of extended high water in the river. Thus, most of the soil profile was saturated for an extended period during the growing season, resulting in an abnormally high amount of N loss. As such, a higher N rate was needed for EONR (270 kg N ha^{-1}). In summary, this analysis showed that SDI was one of the more

TABLE 6 Performance metrics for each hydrologic soil group and drainage class (HGDC) based model for estimating the economic optimal nitrogen rate (EONR) at validation sites. Results shown are for both N timings (at-planting and side-dress)

N time	HGDC delineation	*n*	r^2	Percentage sites within 34 kg N ha^{-1}
At-planting	A and D	–	–	–
	B-WD	22	.16	46
	B-PD	10	.11	44
	C-WD	3	.99	66
	C-PD	24	.09	26
	Overall	59	.19	37
Side-dress	A and D	35	.40	49
	B-WD	14	.15	39
	B-PD	21	.16	52
	C-WD	10	.68	70
	C-PD	26	.11	15
	Overall	106	.25	42

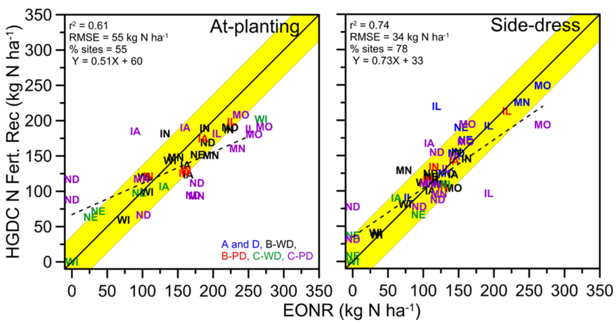

FIGURE 4 Performance of all hydrologic soil group and drainage class (HGDC) based N recommendations compared with the economically optimum nitrogen fertilizer rate (EONR). The dashed line is the resulting regression relationship. The solid diagonal line represents a 1:1 relationship between HGDC recommendations and EONR with sites within the yellow shaded region being within 34 kg N ha^{-1} of EONR. Values are represented by U.S. state abbreviations

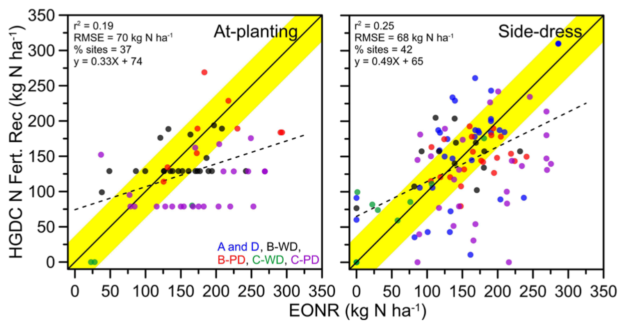

FIGURE 5 Recommended N rate from the models of this analysis (Table 5) as related to the economically optimum nitrogen fertilizer rate (EONR) of the validation sites at two N application timings. Site color matches the hydrologic soil group and drainage class (HGDC) colors found in Figure 1. Measures of performance include coefficient of determination (r^2), root mean square error (RMSE) of the difference between N recommendation and EONR, and percentage of sites within 34 kg N ha^{-1} of EONR (area shown in yellow). Values are represented by U.S. state abbreviations

impactful variables for estimating corn N need even though SDI is difficult to interpret because values do not represent precipitation quantity (i.e., the same SDI value can be derived with different total precipitation amounts).

Using the models reported in Table 5 and illustrated in Figures 2 and 3, N fertilizer recommendations were applied to these same 49 sites and contrasted with actual EONR (Figure 4). Even though doing this utilizes the same data for both developing and testing, it is only an initial evaluation in order to compare with past and future efforts. These HGDC-based models performed better than previous efforts with $r^2 \geq$ .61, RMSE ≤ 55 kg N ha^{-1}, and ≥55% of sites within 34 kg N ha^{-1} of EONR. Whereas previous efforts–which used a minimal number of soil and weather variables to estimate EONR–were only able to achieve results of $r^2 \leq$ .60, RMSE ≥ 50 kg N ha^{-1}, and ≤55% of sites within 34 kg N ha^{-1} of EONR (Bean et al., 2018b; Clark et al., 2020; Qin et al., 2018; Ransom et al., 2020; Ransom, Kitchen, et al., 2021).

3.2 | Validation of models

Using the 181 site-year validation dataset, delineation resulted in 51, 36, 31, 13, and 50 site-years for HGDC A and D, B-WD, B-PD, C-WD, and C-PD, respectively. A total of 16 of the 181 site-years collected were not used for validation analysis as these sites fell within the HGDC A and D at-planting delineation, which had no model (Table 5). Within each HGDC group, there was a large variation in performance for both at-planting and side-dress timings, with the best performance observed in the C-WD group and the worst in the C-

PD group (Figure 5, Table 6). A static outcome was seen in the at-planting HGDC recommendations for individual locations due to the sole dependency on soil variables. These variables (e.g., clay, total C, SOM, and PAWC) are not easily changed from season to season, resulting in the same N fertilizer rate across growing seasons. With weather factors included for the side-dress application timing, recommendations were much more variable.

Overall, considering all the HGDC groups, the performance was promising but still needing improvement with 37 and 42% of sites within 34 kg N ha^{-1} for at-planting and side-dress, respectively. This performance was worse than the model development's outcomes (Figure 4), but compared to what others have reported, results were interesting (Laboski et al., 2014; Ransom et al., 2020). Upon closer examination, several possible reasons exist for this performance difference, the biggest being the need to fill in missing soil information (e.g., respiration) using samples collected in 2018 in order to represent corn yield responses as far back as 2000. We assume performance would have been better if we had the required soil information from the year of the study. Another issue was that some soils information was outside the original range of the model (e.g., one location had 10% SOM, approximately three times higher than any in the original dataset). Additionally, it was difficult to calculate SDI when there was no record of when and how much irrigation was applied–which caused HGDC C-WD models to overestimate EONR. Next, models may have performed better if actual measured soil values had been used to classify sites into HGDC groups rather than SSURGO.

Overall, results of this study show the impact of weather and the difficulty in estimating season long N fertilizer need. And as others have observed, N recommendation tools may be successful in one specific field or during one growing season, but reliably predicting the correct EONR over a spatially and temporally diverse landscape is still difficult (Morris et al., 2018; Scharf et al., 2005; Scharf & Lory, 2009). Lastly, while most of the locations with both the model development and validation datasets were corn rotated after soybean, a few locations were continuous corn. Since rotation was not included (i.e., too few observations), we expect additional improvement had such been included with this analysis.

3.2.1 | Comparing HGDC models with state-specific recommendations

An appropriate comparison would be to examine the HGDC-based model recommendations of this study alongside current state-specific recommendations for those states contributing sites to the validation datasets. This was accomplished by evaluating both N timing recommendations relative to EONR (Figure 6). Using RMSE and percentage of sites within 34 kg N ha^{-1} of EONR, the HGDC model recommendations performed slightly better than state-specific recommendations.

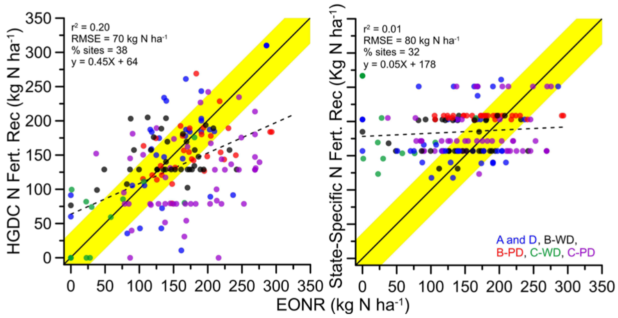

FIGURE 6 Recommended N fertilization rate from the hydrologic soil group and drainage class (HGDC) models (left) and state-specific recommendations tools (right) are shown relative to the economically optimum nitrogen fertilizer rate (EONR) for validation sites (timings combined). Measures of performance include coefficient of determination (r^2), root mean square error (RMSE) of the difference between N recommendation and EONR, and percentage of sites within 34 kg N ha^{-1} of EONR. Sites fall within the yellow shaded region are those within 34 kg N ha^{-1} of EONR. Values are represented by U.S. state abbreviations

Differences between HGDC and state-specific recommendations were apparent. First, few state-specific recommendations fell below 125 kg ha^{-1}, while many HGDC recommendations did. Next, four of the six states in the validation dataset employ the MRTN approach to corn N management (Iowa, Indiana, North Dakota, and Wisconsin). They use N response trials over multiple years and soils within states to generate an average EONR response function. In this way, the MRTN approach is like other state-specific recommendations, where temporal and spatial variability are averaged (Morris et al., 2018). This averaging built into state-specific recommendations results in sites being fixed along horizontal lines in the state-specific panel of Figure 6. In contrast, since four of five in-season HGDC models employ an element of weather (i.e., SDI from planting to side-dress application), greater variability exists with these recommendations.

Generally, state-specific recommendations overestimated N needed for more sites than the HGDC model approach, particularly for sites where EONR was <150 kg N ha^{-1}. An overestimation with state-specific recommendations might be expected since these approaches do not recommend applying N <100 kg N ha^{-1}. Thus, sites needing <100 kg N ha^{-1} or no N were better estimated with HGDC models. Yet for sites where EONR was >150 kg N ha^{-1}, HGDC models resulted in greater underestimation of corn N need compared to state-specific recommendations.

4 | SUMMARY AND CONCLUSIONS

Estimating EONR is challenging due to soil and weather variability. However, increasing the accuracy of N fertilizer recommendations is imperative for sustainable corn N management. Most factors identified in the models as contributing to corn N need included a combination of weather and soil measurements (Figure 3 in Morris et al., 2018). Previous efforts to capture variability with N recommendation tools have focused either on early season soil or plant sampling, spectral sensing of the crop canopy, or soil–crop simulation modeling (Morris et al., 2018). Our approach was novel. Using USDA HGDC as a framework, we examined which soil and weather factors best explained corn N need. The most important soil and weather factors for characterizing N needs in corn production included SOM, clay content, and evenness of rainfall distribution prior to side-dress application. The fact that rainfall evenness (i.e., SDI) was important for side-dress applications for most HGDCs demonstrates the value of utilizing weather and in-season applications to improve N applications.

Overall, HGDC model performance at validation sites was poor compared to the model development sites, but slightly better than current state-specific recommendations. Results were, however, better with some HGDC categories than with others. Those showing strong performance (e.g., C-WD) deserve further attention with additional validation work. Poor performance in some cases may have resulted from samples or information that did not match the same information used for developing the models. For sites where EONR was <100 kg N ha^{-1}, the HGDC models outperformed state-specific recommendations. In contrast, the model predictions would underestimate fertilizer N needs for many sites with EONR above 150 kg N ha^{-1}. Many farmers would not accept recommendations that risk lower yield and income. Regardless, these findings show that over an extensive region, the HGDC framework has potential for improving the accuracy of N fertilizer recommendations and deserves further testing and refinement.

AUTHOR CONTRIBUTIONS

G.M. Bean: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Writing-original draft; Writing-review & editing. C.J. Ransom: Data curation; Investigation; Project administration; Validation; Visualization; Writing-review & editing. N.R. Kitchen: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. P.C. Scharf: Conceptualization; Methodology; Writing-review & editing. K.S. Veum: Methodology; Resources; Writing-review & editing. J.J. Camberato: Data curation; Funding acquisition; Investigation; Methodology; Resources; Validation; Writing-review & editing. R.B. Ferguson: Data curation; Funding acquisition; Investigation; Methodology; Resources; Validation; Writing-review & editing. F.G. Fernandez: Data curation; Funding acquisition; Investigation; Methodology; Resources; Validation; Writing-review & editing. D.W. Franzen: Data curation; Funding acquisition; Investigation; Methodology; Resources; Validation; Writing-review & editing. C.A.M Laboski: Data curation; Funding acquisition; Investigation; Methodology; Resources; Validation; Writing-review & editing. E.D. Nafziger: Data curation; Funding acquisition; Investigation; Methodology; Resources; Validation; Writing-review & editing. J.E. Sawyer: Data curation; Funding acquisition; Investigation; Methodology; Resources; Validation; Writing-review & editing. Robert L. Nielsen: Data curation; Resources; Validation; Writing-review & editing

DATA AVAILABILITY STATEMENT

Data used for model development (49 site-years) is described and made available in supplemental files in Ransom, Clark, et al. (2021) or in a Dryad repository: https://doi.org/10.5061/dryad.66t1g1k2g.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Curtis J. Ransom https://orcid.org/0000-0002-1268-7247
Newell R. Kitchen https://orcid.org/0000-0003-2268-9016
Kristen S. Veum https://orcid.org/0000-0002-6492-913X
James J. Camberato https://orcid.org/0000-0002-6677-854X
Fabián G. Fernández https://orcid.org/0000-0002-9539-0050
David W. Franzen https://orcid.org/0000-0003-4862-8086
Carrie A. M. Laboski https://orcid.org/0000-0003-2050-767X
Emerson D. Nafziger https://orcid.org/0000-0002-6578-1624
Robert L. Nielsen https://orcid.org/0000-0002-7673-1681

REFERENCES

Abendroth, L. J., Elmore, R. W., Boyer, M. J., & Marlay, S. K. (2011). Corn growth and development *(Extension Publication PMR 1009)*. Iowa State University, Agronomy Extension.

Armstrong, R. D., Fitzpatrick, J., Rab, M. A., Abuzar, M., Fisher, P. D., & O'Leary, G. J. (2009). Advances in precision agriculture in south-eastern Australia. iii. Interactions between soil properties and water use help explain spatial variability of crop production in the Victorian Mallee. *Crop and Pasture Science*, *60*(9), 870–884. https://doi.org/10.1071/CP08349

Bandura, C. (2017). *Agronomic and environmental evaluation of nitrogen rate and timing for Midwestern corn production* (Master's thesis, University of Wisconsin). https://search.library.wisc.edu/catalog/9912366352202121

Bean, G. M., Kitchen, N. R., Camberato, J. J., Ferguson, R. B., Fernandez, F. G., Franzen, D. W., Laboski, C. A. M., Nafziger, E. D., Sawyer, J. E., Scharf, P. C., Schepers, J., & Shanahan, J. S. (2018a). Active-optical reflectance sensing corn algorithms evaluated over the United States Midwest Corn Belt. *Agronomy Journal*, *110*(6), 2552–2565. https://doi.org/10.2134/agronj2018.03.0217

Bean, G.M., Kitchen, N. R., Camberato, J. J., Ferguson, R. B., Fernandez, F. G., Franzen, D. W., Laboski, C. A. M., Nafziger, E. D., Sawyer, J. E., Scharf, P. C., Schepers, J., & Shanahan, J. S. (2018b). Improving an active-optical reflectance sensor algorithm using soil and weather information. *Agronomy Journal*, *110*(6), 2541–2551. https://doi.org/10.2134/agronj2017.12.0733

Blackmer, A., Binford, G., Morris T., & Meese, B. (1992). *Effects of rates of nitrogen fertilization on corn yields, nitrogen losses from soils, and energy consumption*. (Extension Publication PM-1467, pp. 20–25). Iowa State University, Agronomy Extension.

Blanchard, P. E., & Lerch, R. N. (2000). Watershed vulnerability to losses of agricultural chemicals: interactions of chemistry, hydrology, and land-use. *Environmental Science & Technology*, *34*, 3315–3322. https://doi.org/10.1021/es991115+

Blevins, D. W., Wilkison, D. H., Kelly, B. P., & Silva, S. R. (1996). Movement of nitrate fertilizer to glacial till and runoff from a claypan soil. *Journal of Environmental Quality*, *25*(3), 584–593. https://doi.org/10.2134/jeq1996.00472425002500030026x

Boyle, M., Frankenberger, W. T., & Stolzy, L. H. (1989). The influence of organic matter on soil aggregation and water infiltration. *Journal of Production Agriculture*, *2*(4), 290–299. https://doi.org/10.2134/jpa1989.0290

Brown, K. H., Bach, E. M., Drijber, R. A., Hofmockel, K. S., Jeske, E. S., Sawyer, J. E., & Castellano, M. J. (2014). A long-term nitrogen fertilizer gradient has little effect on soil organic matter in a high-intensity maize production system. *Global Change Biology*, *20*(4), 1339–1350. https://doi.org/10.1111/gcb.12519

Bu, H., Sharma, L. K., Denton, A., & Franzen, D. W. (2017). Comparison of satellite imagery and ground-based active optical sensors as yield predictors in sugar beet, spring wheat, corn, and sunflower. *Agronomy Journal*, *109*(1), 299–308. https://doi.org/10.2134/agronj2016.03.0150

Buchholz, D. D., Brown, J. R., Crocker, D. K., Garrett, J. D., Hanson, R. G., Lory, J. A, & Nathan, M. V. (2004). *Soil test interpretations and recommendations handbook*. University of Missouri, College of Agriculture, Division of Plant Science.

Clark, J. D., Fernández, F. G., Veum, K. S., Camberato, J. J., Carter, P. R., Ferguson, R. B., Franzen, D. W., Kaiser, D. E., Kitchen, N. R., Laboski, C. A. M., Nafziger, E. D., Rosen, C. J., Sawyer, J. E., & Shanahan, J. F. (2020). Soil-nitrogen, potentially mineralizable-nitrogen, and field condition information marginally improves corn nitrogen management. *Agronomy Journal*, *112*(5), 4332–4343. https://doi.org/10.1002/agj2.20335

Crowther, J. (2018). *Integrating management zones and canopy sensing to improve nitrogen recommendation algorithms* (Master's thesis, University of Nebraska). https://digitalcommons.unl.edu/agronhortdiss/135

Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, *440*(7081), 165–173. https://doi.org/10.1038/nature04514

Dellinger, A. E., Schmidt, J. P., & Beegle, D. B. (2008). Developing nitrogen fertilizer recommendations for corn using an active sensor. *Agronomy Journal*, *100*(6), 1546–1552. https://doi.org/10.2134/agronj2007.0386

Emmert, D. J. (2009). *Using canopy reflectance to monitor corn response to nitrogen and the effects of delayed nitrogen application* (Master's thesis, Purdue University). https://docs.lib.purdue.edu/dissertations/AAI1469842/

Gehl, R. J., Schmidt, J. P., Maddux, L. D., & Gordon, W. B. (2005). Corn yield response to nitrogen rate and timing in sandy irrigated soils. *Agronomy Journal*, *97*(4), 1230–1238. https://doi.org/10.2134/agronj2004.0303

Goreau, T. J., Kaplan, W. A., Wofsy, S. C., McElroy, M. B., Valois, F. W., & Watson, S. W. (1980). Production of NO_2^- and N_2O by nitrifying bacteria at reduced concentrations of oxygen. *Applied and Environmental Microbiology*, *40*(3), 526–532. https://doi.org/10.1128/AEM.40.3.526-532.1980

Hallmark, W. B., & Barber, S. A. (1981). Root growth and morphology, nutrient uptake, and nutrient status of soybeans as affected by soil K and bulk density. *Agronomy Journal*, *73*(5), 779–782. https://doi.org/10.2134/agronj1981.00021962007300050008x

Howard, D. M., & Howard, P. J. A. (1993). Relationships between CO_2 evolution, moisture content and temperature for a range of soil types. *Soil Biology and Biochemistry*, *25*(11), 1537–1546. https://doi.org/10.1016/0038-0717(93)90008-Y

Jeutong, F., Eskridge, K. M., Waltman, W. J., & Smith, O. S. (2000). Comparison of bioclimatic indices for prediction of maize yields. *Crop Science*, *40*(6), 1612–1617. https://doi.org/10.2135/cropsci2000.4061612x

Kablan, L. A., Chabot, V., Mailloux, A., Bouchard, M.-È., Fontaine, D., & Bruulsema, T. (2017). Variability in corn yield response to nitrogen fertilizer in eastern Canada. *Agronomy Journal*, *109*(5), 2231–2242. https://doi.org/10.2134/agronj2016.09.0511

Kitchen, N. R., Shanahan, J. F., Ransom, C. J., Bandura, C. J., Bean, G. M., Camberato, J. J., Carter, P. R., Clark, J. D., Ferguson, R. B., Fernández, F. G., Franzen, D. W., Laboski, C. A. M., Nafziger, E. D., Qing, Z., Sawyer, J. E., & Shafer, M. (2017). A public-industry partnership for enhancing corn nitrogen research and datasets: Project description, methodology, and outcomes. *Agronomy Journal*, *109*(5), 2371–2389. https://doi.org/10.2134/agronj2017.04.0207

Kitchen, N. R., Sudduth, K. A., Drummond, S. T., Scharf, P. C., Palm, H. L., Roberts, D. F., & Vories, E. D. (2010). Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. *Agronomy Journal*, *102*(1), 71–84. https://doi.org/10.2134/agronj2009.0114

Kyveryga, P. M., Blackmer, A. M., & Morris, T. F. (2007). Alternative benchmarks for economically optimal rates of nitrogen fertilization for corn. *Agronomy Journal*, *99*(4), 1057–1065. https://doi.org/10.2134/agronj2006.0340

Laboski, C. A. M., Camberato, J. J., & Sawyer, J. E. (2014). Evaluation of Adapt-N in the Corn Belt. *Proceedings North Central Extension-Industry Soil Fertility Conference*, *30*, 60–67. http://lib.dr.iastate.edu/agron_conf/52

Linn, D. M., & Doran, J. W. (1984). Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Science Society of America Journal*, *48*(6), 1267–1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x

Ma, B. L., Wu, T. Y., Tremblay, N., Deen, W., McLaughlin, N. B., Morrison, M. J., & Stewart, G. (2010). On-farm assessment of the amount and timing of nitrogen fertilizer on ammonia volatilization. *Agronomy Journal*, *102*(1), 134–144. https://doi.org/10.2134/agronj2009.0021

Meisinger, J. J., Schepers, J. S., & Raun, W. R. (2008). Crop nitrogen requirement and fertilization. *Nitrogen in Agricultural Systems*, *49*, 563–612. https://doi.org/10.2134/agronmonogr49.c14

Miller, E. (2012). *Nitrogen application timing and rate effects on nitrogen utilization of corn and the adoption of active optical reflectance sensors for nitrogen management* (Master's thesis, Purdue University). https://docs.lib.purdue.edu/dissertations/AAI1530311/

Moebius-Clune, B. N., Moebius-Clune, D. J., Gugino, B. K., Idowu, O. J., Schindelbeck, R. R., Ristow, A. J., van Es, H. M., Thies, J. E., Shayler, H. A., McBride, M. B., Wolfe, D. W., & Abawi, G. S. (2016). *Comprehensive assessment of soil health: The Cornell framework manual* (edition 3.1). Cornell University.

Morris, T. F., Murrell, T. S., Beegle, D. B., Camberato, J. J., Ferguson, R. B., Grove, J., Ketterings, Q., Kyveryga, P. M., Laboski, C. A. M., McGrath, J. M., Meisinger, J. J., Melkonian, J., Moebius-Clune, B. N., Nafziger, E. D., Osmond, D., Sawyer, J. E., Scharf, P. C., Smith, W., Spargo, J. T., … Yang, H. (2018). Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. *Agronomy Journal*, *110*(1), 1–37. https://doi.org/10.2134/agronj2017.02.0112

Moser, M. E. (2016). *Residual effects of nitrogen fertilization on soil nitrogen pools and corn growth* (Master's thesis, Purdue University). https://docs.lib.purdue.edu/open_access_theses/880/

Nafziger, E. D., Sawyer, J. E. & Hoeft, R. G. (2004). Formulating N recommendations for corn in the Corn Belt using recent data. In B. Hoeft (Ed.) *Proceedings of the North Central Extension-Industry Soil Fertility Conference*, (Vol. 20, pp. 5–11). Potash & Phosphate Institute.

Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. In *Methods of soil analysis: Part 3. Chemical methods* (5th ed., pp. 961–1010). John Wiley & Sons, Ltd.

O'Geen, A., Walkinshaw, M., & Beaudette, D. (2017). SoilWeb: A multifaceted interface to soil survey information. *Soil Science Society of America Journal*, *81*(4), 853–862. https://doi.org/10.2136/sssaj2016.11.0386n

Poffenbarger, H. J., Barker, D. W., Helmers, M. J., Miguez, F. E., Olk, D. C., Sawyer, J. E., Six, J., & Castellano, M. J. (2017). Maximum soil organic carbon storage in Midwest U.S. cropping systems when crops are optimally nitrogen-fertilized. *PLOS ONE*, *12*(3), e0172293. https://doi.org/10.1371/journal.pone.0172293

Power, J. F., Wiese, R., & Flowerday, D. (2001). Managing farming systems for nitrate control: A research review from management systems evaluation areas. *Journal of Environmental Quality*, *30*(6), 1866–1880. https://doi.org/10.2134/jeq2001.1866

Puntel, L. A., Sawyer, J. E., Barker, D. W., Dietzel, R., Poffenbarger, H., Castellano, M. J., Moore, K. J., Thorburn, P., & Archontoulis, S. V. (2016). Modeling long-term corn yield response to nitrogen rate and crop rotation. *Frontiers in Plant Science*, *7*, eLocator. https://doi.org/10.3389/fpls.2016.01630

Puntel, L. A., Sawyer, J. E., Barker, D. W., Thorburn, P. J., Castellano, M. J., Moore, K. J., VanLoocke, A., Heaton, E. A., & Archontoulis, S. V. (2018). A systems modeling approach to forecast corn economic optimum nitrogen rate. *Frontiers in Plant Science*, *9*, 1–15. https://doi.org/10.3389/fpls.2018.00436

Qin, Z., Myers, D. B., Ransom, C. J., Kitchen, N. R., Liang, S. Z., Camberato, J. J., Carter, P. R., Ferguson, R. B., Fernandez, F. G., Franzen, D. W., Laboski, C. A. M., Malone, B. D., Nafziger, E. D., Sawyer, J. E., Shanahan, J. F., Qing, J., & Myers, B. (2018). Application of machine learning methodologies for predicting corn economic optimal nitrogen rate. *Agronomy Journal*, *110*(6), 2596–2607. https://doi.org/10.2134/agronj2018.03.0222

Ransom, C. J., Clark, J., Bean, G. M., Bandura, C., Shafer, M. E., Kitchen, N. R., Camberato, J. J., Carter, P. R., Ferguson, R. B., Fernández, F., Franzen, D. W., Laboski, C. A. M., Myers, D. B., Nafziger, E. D., Sawyer, J. E., & Shanahan, J. (2021). Data from a public–industry partnership for enhancing corn nitrogen research. *Agronomy Journal*. https://doi.org/10.1002/agj2.20812

Ransom, C. J., Kitchen, N. R., Camberato, J. J., Carter, P. R., Ferguson, R. B., Fernández, F. G., Franzen, D. W., Laboski, C. A. M., Nafziger, E. D., Sawyer, J. E., Scharf, P. C., & Shanahan, J. F. (2020). Corn nitrogen rate recommendation tools' performance across eight US Midwest Corn Belt states. *Agronomy Journal*, *112*, 470–492. https://doi.org/10.1002/agj2.20035

Ransom, C. J., Kitchen, N. R., Sawyer, J. E., Camberato, J. J., Carter, P. R., Ferguson, R. B., Fernández, F. G., Franzen, D. W., Laboski, C. A. M., Myers, D. B., Nafziger, E. D., & Shanahan, J. F. (2021). Improving publicly available corn nitrogen rate recommendation tools with soil and weather measurements. *Agronomy Journal*, *113*(2), 2068–2090. https://doi.org/10.1002/agj2.20627

Reeves, D. W., Wood, C. W., & Touchton, J. T. (1993). Timing nitrogen applications for corn in a winter legume conservation-tillage system. *Agronomy Journal*, *85*(1), 98–106. https://doi.org/10.2134/agronj1993.00021962008500010020x

Sawyer, J. E. (2013). Laboski, C., Comparison of the MRTN and Adapt-N derived N rates for corn. *Proceedings of the 43rd North Central Extension-Industry Soil Fertility Conference*. In *Proceedings of the 43rd North Central Extension-Industry Soil Fertility Conference*, (Vol. 29, pp. 60–67). International Plant Nutrition Institute.

Sawyer, J., Nafziger, E., Randall, G., Bundy, L., Rehm, G., & Joern, B. (2006). *Concepts and rationale for regional nitrogen rate guidelines for corn*. Iowa State University-University Extension.

Saxton, K. E., & Rawls, W. J. (2006). Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal*, *70*(5), 1569–1578. https://doi.org/10.2136/sssaj2005.0117

Schaetzl, R., & Anderson, S. (2014). *Soils genesis and geomorphology* (6th printing). Cambridge University Press.

Scharf, P. C., Kitchen, N. R., Sudduth, K. A., Davis, J. G., Hubbard, V. C., & Lory, J. A. (2005). Field-scale variability in optimal nitrogen fertilizer rate for corn. *Agronomy Journal*, *97*(2), 452–461. https://doi.org/10.2134/agronj2005.0452

Scharf, P. C., & Lory, J. A. (2009). Calibrating reflectance measurements to predict optimal sidedress nitrogen rate for corn. *Agronomy Journal*, *101*(3), 615–625. https://doi.org/10.2134/agronj2008.0111

Schröder, J., Neeteson, J., Oenema, O., & Struik, P. (2000). Does the crop or the soil indicate how to save nitrogen in maize production? *Field Crops Research*, *66*(2), 151–164. https://doi.org/10.1016/S0378-4290(00)00072-1

Sela, S., van Es, H. M., Moebius-Clune, B. N., Marjerison, R., & Kneubuhler, G. (2018). Dynamic model-based recommendations increase the precision and sustainability of N fertilization in midwestern US maize production. *Computers and Electronics in*

Agriculture, *153*(August), 256–265. https://doi.org/10.1016/j.compag.2018.08.010
Setiyono, T. D., Yang, H., Walters, D. T., Dobermann, A., Ferguson, R. B., Roberts, D. F., Lyon, D. J., Clay, D. E., & Cassman, K. G. (2011). Maize-N: A decision tool for nitrogen management in maize. *Agronomy Journal*, *103*(4), 1276–1283. https://doi.org/10.2134/agronj2011.0053
Shanahan, J. F., Kitchen, N. R., Raun, W. R., & Schepers, J. S. (2008). Responsive in-season nitrogen management for cereals. *Computers and Electronics in Agriculture*, *61*(1), 51–62. https://doi.org/10.1016/j.compag.2007.06.006
Shahandeh, H., Wright, A. L., & Hons, F. M. (2011). Use of soil nitrogen parameters and texture for spatially-variable nitrogen fertilization. *Precision Agriculture*, *12*(1), 146–163. https://doi.org/10.1007/s11119-010-9163-8
Shapiro, C. A., Ferguson, R. B., Hergert, G. W., Wortmann, C. S., & Walters, D. T. (2008). *Fertilizer suggestions for corn* (Extension publication EC117). Nebraska Extension.
Sharma, L. K., Bali, S. K., Zaeen, A. A., Baldwin, P., & Franzen, D. W. (2018). Use of rainfall data to improve ground-based active optical sensors yield estimates. *Agronomy Journal*, *110*(4), 1561–1571. https://doi.org/10.2134/agronj2017.12.0696
Shaw, L. H. (1964). The effect of weather on agricultural output: A look at methodology. *Journal of Farm Economics*, *46*(1), 218. https://doi.org/10.2307/1236485
Soil Survey Staff. (2014). *Soil survey field and laboratory methods manual* (Soil Survey Investigators Report no. 51). United States Department of Agriculture, Natural Resources Conservation Service.
Teeter, A. O. (2019). *Evaluating the use of cover crop and nitrapyrin to improve manure nitrogen availability to corn* (Master's thesis, University of Wisconsin). https://search.library.wisc.edu/catalog/9912923436302121
Thompson, L. J., Ferguson, R. B., Kitchen, N. R., Franzen, D. W., Mamo, M., Yang, H., & Schepers, J. S. (2015). Model and sensor-based recommendation approaches for in-season nitrogen management in corn. *Agronomy Journal*, *107*(6), 2020–2030. https://doi.org/10.2134/agronj15.0116
Tremblay, N. (2004). Determining nitrogen requirements from crops characteristics. benefits and challenges. *Recent Research Developments in Agronomy & Horticulture*, *1*, 157–182.
Tremblay, N., & Bélec, C. (2006). Adapting nitrogen fertilization to unpredictable seasonal conditions with the least impact on the environment. *HortTechnology*, *16*(3), 408–412. https://doi.org/10.21273/HORTTECH.16.3.0408
Tremblay, N., Bouroubi, Y. M., Bélec, C., Mullen, R. W., Kitchen, N. R., Thomason, W. E., Ebelhar, S., Mengel, D. B., Raun, W. R., Francis, D. D., Vories, E. D., & Ortiz-Monasterio, I. (2012). Corn response to nitrogen is influenced by soil texture and weather. *Agronomy Journal*, *104*(6), 1658–1671. https://doi.org/10.2134/agronj2012.0184
Ullah, S., & Moore, T. R. (2009). Soil drainage and vegetation controls of nitrogen transformation rates in forest soils, southern Quebec. *Journal of Geophysical Research: Biogeosciences*, *114*, G01014. https://doi.org/10.1029/2008JG000824
USDA NRCS. (2009). Hydrologic soil groups. Hoeft, C. C., *Part 630 National Engineering Handbook*. In *Part 630 National Engineering Handbook*. USDA Soil Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/hydrology/?cid=stelprdb1043063
Williams, J. D., Crozier, C. R., White, J. G., Heiniger, R. W., Sripada, R. P., & Crouse, D. A. (2007). Illinois soil nitrogen test predicts southeastern U.S. corn economic optimum nitrogen rates. *Soil Science Society of America Journal*, *71*(3), 735–744. https://doi.org/10.2136/sssaj2006.0135
Williams, A., Hunter, M. C., Kammerer, M., Kane, D. A., Jordan, N. R., Mortensen, D. A., Smith, R. G., Snapp, S., & Davis, A. S. (2016). Soil water holding capacity mitigates downside risk and volatility in US rainfed maize: Time to invest in soil organic matter? *PLOS ONE*, *11*(8), e0160974. https://doi.org/10.1371/journal.pone.0160974
Xie, M., Tremblay, N., Tremblay, G., Bourgeois, G., Bouroubi, M. Y., & Wei, Z. (2013). Weather effects on corn response to in-season nitrogen rates. *Canadian Journal of Plant Science*, *93*(3), 407–417. https://doi.org/10.4141/cjps2012-145
Yamoah, C. F., Francis, C. A., Varvel, G. E., & Waltman, W. J. (1998). Weather and management impact on crop yield variability in rotations. *Journal of Production Agriculture*, *11*(2), 219–225. https://doi.org/10.2134/jpa1998.0219
Yost, M. A., Veum, K. S., Kitchen, N. R., Sawyer, J. E., Camberato, J. J., Carter, P. R., Ferguson, R. B., Fernández, F. G., Franzen, D. W., Laboski, C. A. M., & Nafziger, E. D. (2018). Evaluation of the Haney Soil Health Tool for corn nitrogen recommendations across eight Midwest states. *Journal of Soil and Water Conservation*, *73*(5), 587–592. https://doi.org/10.2489/jswc.73.5.587
Zhu, Q., Schmidt, J. P., Lin, H. S., & Sripada, R. P. (2009). Hydropedological processes and their implications for nitrogen availability to corn. *Geoderma*, *154*(1–2), 111–122. https://doi.org/10.1016/j.geoderma.2009.10.004
Zibilske, L. (1994). Carbon mineralization. In R. W. Weaver, J. S. Angle, & P. J. Bottomley (Eds.), *Methods of soil analysis. Part 2. Microbiological and biochemical properties* (pp. 835–864). SSSA. https://acsess.onlinelibrary.wiley.com/doi/abs/10.2136/sssabookser5.2.c38

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Bean, G. M., Ransom, C. J., Kitchen, N. R., Scharf, P. C., Veum, K. S., Camberato, J. J., Ferguson, R. B., Fernandez, F. G., Franzen, D. W., Laboski, C. A. M., Nafziger, E. D., Sawyer, J. E., & Nielsen, R. L. (2021). Soil hydrologic grouping guide which soil and weather properties best estimate corn nitrogen need. *Agronomy Journal*. *113:*5541–5555. https://doi.org/10.1002/agj2.20888