Factors Affecting Nitrogen Availability and Variability in Cornfields

Haiying Tao,* Thomas F. Morris, Peter Kyveryga, and John McGuire

ABSTRACT
Nitrogen management in corn (Zea mays L.) is complicated by uncertainties in the agro-ecological system. Consequently, current N recommendation systems provide accurate estimates of average N rates to apply across geographic regions but not to individual fields. To improve N use efficiency (NUE) and reduce negative environmental impacts, field-specific N rates should be estimated using site factors that can have significant effects on N loss and availability. We surveyed 920 cornfields across the US Corn Belt and collected 3680 cornstalk samples during a 7-yr period, 2008 to 2014. Aerial images of the corn canopies taken in late August were used to randomly select three sampling areas within three predominant soil types in each field. Cornstalk samples were evaluated for N status using the end-of-season cornstalk nitrate test (CSNT). We also collected data about site-specific environmental conditions and management practices that had the potential to influence N loss and availability. Ordinal logistic regression (OLR) analysis was used to identify factors that significantly affected cornstalk N-sufficiency levels, based on the CSNT. Results suggest that N rate alone is not a driving factor that influences N availability to a corn plant during the growing season. Rather, N rate recommendations should be estimated considering other site factors, including rainfall, previous crop, tillage practice, soil drainage class, and N form and timing. Our research findings are useful to support a field-based adaptive management program and the 4Rs of Nutrient Stewardship management.

Core Ideas
• N application rate for corn should be estimated conditional to other influential factors to N availability.
• Guided sampling by aerial imagery for end-of-season stalk nitrate-N test is a useful tool to benchmark N variability.
• N availability for corn is significantly affected by crop rotation, tillage, soil, and N form, rate, and timing.

As the leading producer of corn, the United States harvested 36.4 million ha in 2015, representing about 31% of worldwide production (FAS-USDA, 2017). A significant portion (83%) of this corn was planted across an area of the US Midwest known as the Corn Belt. Nitrogen is usually the largest fertilization expense in corn production in the Corn Belt and, compared with other nutrients, has the greatest effect on yield and profitability. Unfortunately, N fertilizer also presents the largest risk to the environment, compared with other fertilizers, because of its high water solubility and easy transformation into nitrous oxide ($\text{N}_2\text{O}$)—one of the primary greenhouse gases. Consequently, careful management of N fertilizer is extremely important to ensure environmental quality and profitable corn production.

Managing N fertilizer in corn production for both profitability and environmental quality is extremely difficult for farmers. For example, many factors outside the farmers’ control can greatly affect the profits from using N fertilizers and the environmental footprint associated with that use. Some of these factors include extreme rainfall events, environmental regulation changes, ongoing sustainability and water quality concerns, and large corn and N fertilizer price fluctuations (Darnhofer et al., 2010; Schaap et al., 2011). These factors also partially explain why N use efficiency (NUE) in corn production remains low—typically 30 to 50%—and has not improved much in the past 20 yr (Cassman et al., 2002; Lassaletta et al., 2014). Furthermore, this low NUE occurs despite much research that is focused on matching fertilizer applications to crop requirements and efforts to improve N fertilizer recommendations. As a result, inefficient and ill-advised N use in corn could partially contribute to a major nonpoint source of environmental N contamination (Chen et al., 2010; Küstermann et al., 2010).

To help farmers and crop advisors develop and implement better nutrient management strategies, the 4Rs of Nutrient Stewardship (International Plant Nutrition Institute [IPNI], 2012) is being promoted. The 4Rs concept emphasizes the importance of the Right source (fertilizer type/form matches crop need), Right rate (fertilizer amount matches crop need), Right time (nutrient availability coincides with crop need), and Right place (fertilizer applications are located for optimal crop use) in
fine-tuning field-by-field nutrient management (http://www.nutrientstewardship.com/4rs). Practically, however, using the 4Rs concept to improve field-based fertilizer decisions is difficult because a limited amount of research has quantified the effects of these R factors and their interactions on N status in farmers’ fields, corn yield and profitability (Kyveryga and Blackmer, 2013). Furthermore, managing N so that crop yield is maximized, and N loss is minimized requires greater scientific understanding of complex agroecosystems at the spatial scale of the individual field.

The paucity of information about managing N at the field scale has created much uncertainty for farmers when deciding the best N rate to apply (Lobell, 2007; Babcock, 1992). Reducing uncertainties in N recommendations for individual fields could significantly increase NUE (Lobell, 2007). Current N recommendation systems provide a high level of confidence for achieving profitable yields, on average, across many fields and years; however, these methods are not suited for individual or field-specific recommendations (Nafziger et al., 2004; Holland and Schepers, 2010). For example, the yield-goal method (Stanford, 1973) has been challenged for the following reasons: (i) poor relationship between recommended rates and observed economic optimum N rates (EONR); (ii) uncertainty associated with defining a reasonable yield goal; (iii) lack of appropriate adjustment for on-farm, non-commercial fertilizer N sources; and (iv) ignoring the effect of hybrids and spatial and temporal variability (Arnal et al., 2013; Blackmer et al., 1997; Bundy, 2000; Chang et al., 2004; Fox and Piekielek, 1995; Grove and Schwab, 2006; Lory and Scharf, 2003; Shanahan et al., 2008). The most commonly used alternative to yield-goal-based N recommendations—the maximum return to N (MRTN) method—adjusts N rates for geographic location and corn and N fertilizer prices (Nafziger et al., 2004). The MRTN provides general fertilizer N needs and the most profitable average N rate. But, the MRTN cannot predict field-specific N requirements or provide accurate estimates of optimum N rates for different management practices or climate conditions across years (Sawyer et al., 2006).

Estimating N application rates is challenging. The amount of N mineralized by soil organic matter (SOM) and the amount lost from mineralized N and N applications occurs through many pathways and transformations, which are affected by many interacting factors (Shumway et al., 2012; Cassman et al., 2002). For example, previous research has shown that N loss and availability can be significantly influenced by spring rainfall (Balkcom et al., 2003); previous crop (Blackmer et al., 1997); soil properties (Tremblay et al., 2012; Blackmer et al., 1997); crop N demand (Cassman et al., 2002); field management practices (Shumway et al., 2012); and N form (Kyveryga et al., 2007), timing (Scharf et al., 2002; Vetsch and Randall, 2004), and placement (Holland and Schepers, 2010; Vanotti and Bundy, 1994a, 1994b).

Additionally, field-based research to quantify relationships between site-specific management practices and N availability for corn requires large datasets. This labor-intensive effort is necessary because corn farmers in the US Midwest commonly use several practices, in varying combinations (Kyveryga et al., 2010), which also interact with soil properties and the timing and amount of rainfall. Traditional small-plot research methods are unable to provide reliable estimates of the relationships between the N status of corn and field practices of farmers or weather. Moreover, small-plot methods are unable to estimate changes in N status due to soil differences within (Malzer et al., 1996; Mamo et al., 2003; Scharf et al., 2005) and among fields (Bundy and Andraski, 1995; Schmitt and Randall, 1994), and weather variability across large geographic regions (Kyveryga et al., 2013). Thus, to improve field-level N recommendations, new research methods are needed that can: (i) efficiently conduct large-scale sampling and observations across many fields, and (ii) quantify N availability under a variety of management scenarios and environmental conditions.

In a previous 2-yr study conducted in production cornfields in Iowa (Kyveryga et al., 2010), we used a new and relatively inexpensive method to quantify relationships among N availability, management practices, and environmental conditions. We designed a unique survey to evaluate corn N sufficiency levels in 683 fields that represented the major N management practices across Iowa. The survey uses aerial imagery and digital soil maps to guide cornstalk sampling for the cornstalk nitrate test (CSNT)—a reliable end-of-season evaluation tool for corn N status (Binford et al., 1990, 1992; Hooker and Morris, 1999; Brouder et al., 2000; Fox et al., 2001; Wilhelm et al., 2005). The CSNT measures the nitrate (NO₃⁻) concentration in the 20.3 to 35.6 cm (8–14 inch), above-ground portion of cornstalks, which can be collected any time from about the 25% milk line stage of growth to 3 wk after black layer formation. The CSNT results are usually categorized into four N sufficiency levels for corn growth: (i) deficient (<250 mg kg⁻¹), (ii) marginal (250–700 mg kg⁻¹), (iii) optimal (700–2000 mg kg⁻¹), and (iv) excessive (>2000 mg kg⁻¹) (Binford et al., 1990, 1992; Blackmer and Mallarino, 1996).

The results from the Iowa study identified several major factors influencing N availability and loss by finding significant relationships between CSNT-based N sufficiency levels and cumulative spring rainfall (March-May), management practices (e.g., crop rotation; tillage; and N rate, form, and timing), and soil properties (e.g., drainage class or soil type) (Kyveryga et al., 2010). An earlier study in Iowa also found a significant relationship between CSNT-based N sufficiency and spring rainfall (Balkcom et al., 2003). Because of regional differences, understanding how these factors affect N status and loss levels is necessary. Specifically, to be adopted by Corn Belt farmers, our new method must prove to be regionally adaptable and N availability relationships and management practices must be regionally and locally evaluated and defined. Thus, the objectives for the study reported herein were to: (i) apply the same field survey and modeling strategy across a wider range of soil, weather, and management conditions in four other corn-producing states, and (ii) extend the data collection period for a total of 7 yr. We anticipate that the study results from these five states (including Iowa) will improve our understanding of the factors that have major effects on N availability. Quantifying these effects can help scientists target the most influential factors and their interactions in future studies and help farmers and farm consultants make more informed and better management and N application rate decisions.
**MATERIALS AND METHODS**

**Site Selection**

The study was conducted in various counties across the Corn Belt states of Ohio (OH), Indiana (IN), Illinois (IL), and Michigan (MI), from 2008 to 2014 (Fig. 1; Table 1). We identified potential participating farms by asking for volunteers through mail surveys, which were sent at least two months before cornstalk sampling. Volunteer selection was based on farmers’ interests in on-farm evaluation of their N management and the proximity of independent crop consultants or agronomists from local cooperatives who were also willing to participate. Cornfields in each farm were selected randomly by farmers or local crop consultants and agronomists. Field locations were either identified on legal land-ownership maps or based on field boundaries that we created using Google Earth (Google Inc., Mountain View, CA) or ArcView 3.3 software (Environ. Syst. Res. Inst., Redlands, CA). All locations and boundaries were confirmed by the participating farmers. Together, the 920 cornfields in the study represented a variety of typical nutrient management practices in the region.

**Field Delineation and Aerial Imagery**

To capture across- and within-field variability in corn N sufficiency levels, we created field maps for all 920 cornfields. ArcGIS-generated field boundary shape files and detailed field information were used by commercial remote-sensing services to develop flight plans for obtaining aerial images of each field. The field images were captured by digital cameras mounted on fixed-wing aircraft at an altitude of 1524 m (5000 feet) on clear days (i.e., with as little cloud interference as possible) in mid- to late-August each year. We chose this time period to coincide with corn reproductive (R) growth stages, R1 to R2, corresponding to the beginning of silking through blister, which occurs approximately 3 wk after silking. Aerial images were captured with a high resolution (0.5–1 m), 4-band digital camera equipped with blue, green, red, and near-infrared filters. The captured wavelengths included the blue band at 410 to 490 nm, green band at 510 to 590 nm, red band at 610 to 690 nm, and near-infrared band at 800 to 900 nm. High processing standards were used to optimize tonal balance, feature alignment, and horizontal accuracy of the aerial images. The green band images were used to differentiate the variability in cornstalk greenness caused by N stress due to other factors such as weeds, pests, diseases, or water insufficiency (Kyveryga et al., 2010).

**Field Sampling Area Identification**

Guided by digital soil maps (downloaded from USDA-NRCS Geospatial Data Gateway, http://datagateway.nrcs.usda.gov/) and aerial imagery, we selected four sampling areas in each of the 920 fields, for a total of 3680 cornstalk sampling sites. By evaluating the soil-type polygons depicted on the soil maps, we identified the three predominant soil types within each field. In ArcGIS, the coinciding aerial image was overlain onto the soil polygon map to choose sampling areas representative of the corn canopy color in each of the three predominant soil types. Then, one cornstalk-sampling site was randomly selected in each soil type, for a total of three sites per field. A fourth sampling site in each field was selected in a yellow- or light-green-colored canopy area, if present (Fig. 2). At cornstalk-sampling time, the sampling locations were uploaded to a handheld GPS, which was then used to navigate to the sampling coordinates within each field. The fourth sample was used to decide whether the stress associated with the yellow canopy color was due to N deficiency or some other factors such as a weed infestation or water stress. The fourth sample was not included in statistical analyses unless specified. Information about this sample, for instance how within-field canopy color variability relates to N availability, was used for educational purposes when meeting with farmers during the study period.

![Fig. 1. Location of surveyed fields in 2008 to 2014.](image)

![Table 1. Study area by state, number of sites, number of end-of-season cornstalk nitrate test (CSNT) samples collected, and year of data collection.](table)
Cornstalk Sampling

We sampled cornstalks after corn plants reached the black layer stage, which occurred approximately 1 wk before harvest. Each sample was a composite of 10, 20.3-cm segments of cornstalk, collected along two corn rows that spanned an area of 6 × 8 m. Each 20.3-cm cornstalk segment was cut beginning at the 15.2-cm mark above ground. Leaves were removed from the stalks. Samples were placed into cloth or paper bags and immediately shipped to commercial laboratories for CSNT analysis.

N Management Data Collection

All fields in this study were managed by the farmers using their typical management practices. That is, we did not ask for changes to management practices for the project. Farmers and consultants collected field-specific management records, including crop rotations; irrigation practices; N inhibitor use; cover crop plantings; tillage methods and timing; manure application history before the current growing season; manure application form, rate, and timing for the current growing season; and rate, form (anhydrous ammonia [AA], urea ammonium nitrate [UAN], others), and timing (fall, spring pre-plant, or in-season sidedress) of inorganic N fertilizer applications. All field records were uploaded to a user-friendly database created for the project by a professional software company. Data input was completed by the end of December for each year of the study. Data were analyzed between December and January to ensure extension and education materials were developed in time for winter meetings.

Rainfall and Soil Information

We obtained 4-km-grid resolution, radar maps of daily rainfall from the National Climate Data Center archive of global historical weather and climate data (http://www.ncdc.noaa.gov/cdo-web/). The daily values for each month were aggregated into monthly, cumulative spring rainfall (March through May) and cumulative growing season rainfall (March through August). Each sampling location was assigned one rainfall value from the closest grid by overlaying the rainfall map and the sampling location map. Soil type, drainage class, and SOM data were obtained from the SSURGO georeferenced digital soil maps for each county, available for download from USDA-NRCS Geospatial Data Gateway (http://datagateway.nrcs.usda.gov/).

Statistical Analysis

We used ordinal logistic regression (OLR) to identify factors that had significant effects on N sufficiency level and to quantify the magnitude of those effects. The OLR model is also known as the proportional odds or cumulative odds model and is used when the response variable is expressed as several ordered categories (Agresti, 2010). The CSNT sufficiency level is expressed as ordered categories—deficient, marginal, optimal, excessive—and served as the response variable in our OLR models.

In the OLR model, the odds of events are defined as the probability that the event will occur divided by the probability that the event will not occur. In our study, an odds ratio was calculated by dividing the odds of one category by the odds of another or reference category. Because CSNT values were categorized into four sufficiency levels (categories), the odds ratio becomes an estimation of the cumulative probability that a cornstalk sample will test in a higher CSNT sufficiency level (category). For example, the model determined the odds of testing in the marginal, optimal, or excessive category versus the deficient category, given a choice between two options for a particular explanatory variable (e.g., tillage versus no tillage), while holding all other explanatory variables constant. With the assumption of parallel regression (equal slopes), the OLR model can simultaneously estimate the cumulative probability of an event from multiple equations. The number of equations in the model equals one less than the number of categories associated with the dependent (response) variable (Hosmer and Lemeshow, 2000; McCullagh, 1980).

If an odds ratio tested significant, the values were interpreted as follows: (i) odds ratio >1, a cornstalk has a higher chance to test in a higher CSNT sufficiency level; (ii) odds ratio <1, a cornstalk has a lower chance to test in a higher CSNT sufficiency level; or (iii) odds ratio = 1, a cornstalk has an equal chance to test in a higher CSNT sufficiency level. The magnitude (odds ratio value) and direction (higher, lower, or equal) of probability were interpreted relative to the reference chosen from the two options of the explanatory variable comparison (Agresti, 2010).

We used the PROC SURVEYLOGISTIC procedure with a specification of LOGIT link in SAS software to estimate parameters for the OLR models (SAS Institute, 2005). We fit multiple models using factors that could have significant effects on CSNT. The best model was selected based on the smallest value for Akaike Information Criteria (AIC) and the largest value for Somers’D and c-c statistics, while satisfying the equal slope assumption (Kyvernyga et al., 2010).

RESULTS AND DISCUSSION

Descriptive Statistics for Variables in the OLR Models

N Application Rate

Farmers applied N fertilizer at a wide range of rates. Almost one-half of the 920 fields (43%) received N rates between 168 and 224 kg ha⁻¹, and 78% of fields received N rates between 168 and 280 kg ha⁻¹ (Table 2). In this analysis, we grouped N rates into five application ranges: <112, 112 to 168, 168 to 224, 224 to 280, and >280 kg ha⁻¹ to reflect typical N application rates in corn.
Table 2. Descriptive statistics of explanatory variables (factors) that had a significant effect on end-of-season cornstalk nitrate test (CSNT) values of 2760 cornstalk samples. Samples were collected from 920 fields across the states of OH, IL, IN, and MI during 2008 to 2014. Parenthetical values are the standard deviation.†

<table>
<thead>
<tr>
<th>Factor</th>
<th>Percentage of total samples‡</th>
<th>Mean N rate‡ (kg ha⁻¹)</th>
<th>CSNT test category‡</th>
<th>%</th>
<th>Deficient</th>
<th>Marginal</th>
<th>Optimal</th>
<th>Excessive</th>
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<td>24</td>
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<td>20</td>
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<td>15</td>
<td>14</td>
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<td>42</td>
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<td>32</td>
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<td>&gt;280</td>
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<td>N timing × form§</td>
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<tr>
<td>Fall AA</td>
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<td>43</td>
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<td>22</td>
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<td>Soil drainage class††</td>
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<td>Poorly drained</td>
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<td>216 (56)</td>
<td>41</td>
<td>18</td>
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Average rainfall across all site years

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<tr>
<td>June</td>
<td>104 (64)</td>
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</tr>
<tr>
<td>March–May (spring)</td>
<td>291 (86)</td>
<td></td>
</tr>
<tr>
<td>March–August (season)</td>
<td>559 (120)</td>
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</table>

† Three out of four CSNT values taken from three dominant soil types in each field are used for analysis. The fourth sample in each field is taken in the stressed area with yellow canopy color, which was only used for educational purpose to show the farmers how stress can affect CSNT.
‡ Mean N rate = mean N application rate in the category. % = percentage of samples that tested in each category for individual year for the “year” factors and the percentage of samples that tested in each category for each other explanatory factor for all 7 yr combined.
§ Fall AA = anhydrous ammonium applied in fall; Sidedress AA = anhydrous ammonium applied as sidedress; Sidedress UAN = urea ammonium nitrate applied as sidedress; Spring AA = anhydrous ammonium applied in spring as pre-plant; Spring UAN = urea ammonium nitrate applied in spring.
¶ Tilled = strip tillage and chisel tillage in spring and/or fall. No-Till = no tillage.
†† Well drained = including excessively drained, well drained, and moderately well drained soils; Poorly drained = including somewhat poorly drained, poorly drained, and very poorly drained soils.
‡‡ Yes = N inhibitor was applied with fertilizer N; No = N inhibitor was not applied with fertilizer N. N inhibitors used in the studied fields included Agrotain (by Koch Agronomic Services, LLC), a urease inhibitor applied with UAN; Instinct (by Dow AgroSciences), a nitrification inhibitor applied with UAN; and N-Serve (by Dow AgroSciences), a nitrification inhibitor applied with AA.
production across the study region. These ranges allowed us to estimate the odds of N sufficiency for farmers’ interest in reducing or increasing N application rates by 56 kg ha⁻¹ on average.

**N Timing and Form**

The timing and form of N for each field represents the timing and form of the majority of the N applied during the growing season (Table 2). Most farmers applied N as sidedress, between the V3 and V6 stages of corn growth, in the form of either AA (24%) or UAN (43%). About 19% of fields received fall N applications in the form of AA. Farmers were advised to apply AA in the fall only when temperatures in the surface 4 inches of soil measured <50°F (Sawyer, 2015; Stewart and Camberato, 2010). The remainder of the fields received spring AA (6%) or UAN (8%), applied in early spring before planting.

**Crop Rotation and Tillage**

Most of the fields were managed as a soybean-corn rotation (79%), followed by corn–corn (15%) and wheat–corn (5%) rotations. Seventy-six percent of the fields were tilled using strip tillage and chisel tillage in spring and/or fall. The remaining 24% of the fields were managed as no-till.

**Soil Drainage Class**

Soil drainage class varied across the study area from excessively drained to very poorly drained. The percentage of cornstalk samples collected from different soil drainage classes were: excessively drained (1%), well drained (12%), moderately well drained (16%), somewhat poorly drained (36%), poorly drained (19%), and very poorly drained (16%). We combined the drainage classes into two categories in the OLR models: well drained (excessively drained, well drained, and moderately well drained) and poorly drained (somewhat poorly, poorly, and very poorly drained). We justified this regrouping because excessively, well, and moderately well drained soils had similar odds for the CSNT sufficiency categories. Likewise, the somewhat poorly, poorly, and very poorly drained soils had similar odds. In addition, we compared model fitness and found no significant differences ($P > 0.10$) between the model that included the six drainage classes and the model that included the two regrouped drainage categories.

**N Inhibitor Use**

In 2013 and 2014, we included N inhibitor use in the model parameters. In these 2 yr, we obtained N inhibitor data (approximately 1100 samples) from fields in OH, IL, and MI. Farmers used a variety of inhibitors including Agrotain (Koch Agronomic Services, LLC), a urease inhibitor applied with UAN; Instinct (Dow AgroSciences), a nitrification inhibitor applied with UAN; and N-Serve (Dow AgroSciences), a nitrification inhibitor applied with AA. Among the fields with N inhibitor applications, 50% received the inhibitor with fall AA. The other 50% received an N inhibitor with either sidedress AA, sidedress UAN, spring AA, or spring UAN.

**Rainfall**

Rainfall during the growing seasons (March through August) for the 17 state-year combinations in this study was fairly evenly distributed, with above-normal rainfall for seven state-year combinations and below-normal rainfall for seven state-year combinations. One state-year combination, Indiana in 2011, received rainfall amounts much below-normal. Spring rainfall (March through May) for the 16 state-year combinations was more likely to be above normal, with nine state-year combinations receiving above-normal, four state-years receiving below-normal, and two state-years receiving normal rainfall.

**N Rates and Management Practices**

Mean N application rates differed among several management practices. For example, in fields that primarily received the AA form of N fertilizer, the mean N rate was 24 kg ha⁻¹ greater than in fields that primarily received the UAN form of N (Table 2). When farmers applied AA to fields in the spring, the mean N rate was 29 kg ha⁻¹ greater than when farmers applied UAN to fields in the spring. Similarly, the mean rate of N for AA sidedress applications was 20 kg ha⁻¹ greater than in fields with UAN sidedress applications. Fields managed as corn–corn and wheat–corn rotations received similar mean N application rates (236 and 239 kg ha⁻¹, respectively), whereas fields managed as soybean–corn rotations received less N fertilizer, with a mean N rate of 208 kg ha⁻¹ (Table 2).

**CSNT Values**

For all studied factors across all states and years, CSNT values varied markedly from 1 to 15,300 mg kg⁻¹, with a geometric mean of 1330 mg kg⁻¹ (Fig. 3). The mean CSNT value for cornstalks sampled from the yellow- or light green-colored canopy areas was 65% lower than the mean value for cornstalks sampled from the representative green-colored canopy areas. Of the samples collected in the yellow- or light green-colored canopy areas, 56% exhibited CSNT values in the deficient category compared with 34% of the samples collected from the green canopy areas. On the other hand, 25% of the samples from the yellow- or light green-colored canopies tested in the excessive category, indicating that corn growing in these areas was stressed by factors other than N deficiency. In most cases, the consultants or farmers could attribute this stress to pests, disease, water deficiency, and waterlogged conditions in the spring, for example. These results...
illustrate that guided CSNT sampling using canopy imagery can help detect the likely causes of stress and N sufficiency level.

The percentage of cornstalk samples that tested in different CSNT N sufficiency levels varied from year to year and across explanatory factors of N application rate, N form and timing, previous crop, tillage, soil drainage, and use of N inhibitors (Table 2). We observed the greatest variation in the percentage of samples that tested in the deficient and excessive categories. In contrast, for the marginal and optimal categories, both the variation in percentage of samples and the average percentage across years and across factors were much smaller. For example, the percentage of samples that tested in deficient, marginal, optimal, and excessive categories varied from 22 to 59, 12 to 21, 14 to 24, and 12 to 41%, respectively, from 2008 to 2014. The percentage of samples that tested in the deficient category decreased, while the percentage of samples that tested in the excessive category increased, as N application rate increased from <112 kg ha⁻¹ (lowest rate applied) to >280 kg ha⁻¹ (highest rate applied).

Factors that Significantly Influence CSNT N Sufficiency Levels

Three types of factors had significant effects on N sufficiency levels. One type of factors is changeable by farmers, such as crop rotation practice, tillage, and N application rate, form, and timing. The second type of factors is unchangeable by farmers but their effects can be minimized by implementing specific management practices. For example, although soil drainage class is an inherent characteristic, N loss can be minimized via the right N form and timing. Applying all N in fall in well drained sandy soils has a higher chance for N loss through leaching (Chalk et al., 1975; Vetsch and Randall, 2004; Wang et al., 2014), while applying N in heavy rainfall seasons in poorly drained soils has a higher probability for N loss through denitrification (Sawyer, 2007). Rainfall is the most important unchangeable factor and its negative effects can be minimized via the right N application timing and by using N stabilizers. The third type of factors is both unpredictable and unmanageable by farmers. For example, the factor year, encompasses multiple, influential variables that interact with N use efficiency or N relocation to grain such as pest outbreaks (Beegle, 2009), or annual variability in soil N mineralization (Cameron et al., 2013).

### Year

The factor, year, had an inconsistent effect on the cumulative probability of cornstalks to test in a higher CSNT category (Table 3). For example, we observed significant odds ratio values for 2008, 2010, and 2014, but not for 2009, 2011, and 2013 in reference to 2012. Yearly differences in CSNT values could be attributed to variables that differed annually, but were not included in the model. For example, different corn varieties, which farmers often vary from year to year, can have different NUEs (Subedi and Ma, 2005). Also, high-intensity, individual rainfall events were not captured in our cumulative rainfall estimates for the growing season; but, these events can significantly increase N leaching losses (Wang et al., 2014). And, pest outbreaks can cause lower yields and, in turn, underutilization of the fertilizer application, resulting in excess N accumulation in the crop (Beegle, 2009). Other factors that affect SOM mineralization, such as spring temperatures or rewetting of soil after

### Table 3. Ordinal logistic regression (OLR) results, evaluating the effects of explanatory variables (factors) on the cumulative probability of end-of-season cornstalk samples to test in a higher cornstalk nitrate test (CSNT) category. Data are based on 2760 samples from 920 fields across the states of OH, IN, IL, and MI during a 7-yr period, 2008 to 2014.†

<table>
<thead>
<tr>
<th>Factor</th>
<th>Options/ conditions‡</th>
<th>Odds ratio</th>
<th>95% Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>2.62*</td>
<td>1.77–3.88</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>1.15</td>
<td>0.68–1.96</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>0.66*</td>
<td>0.44–0.99</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>1.23</td>
<td>0.78–1.93</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>1.36</td>
<td>0.95–1.93</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>2.45*</td>
<td>1.52–3.95</td>
<td></td>
</tr>
<tr>
<td><strong>2012</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N application rate, kg ha⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;112</td>
<td>0.66*</td>
<td>0.46–0.93</td>
<td></td>
</tr>
<tr>
<td>112–168</td>
<td>0.93</td>
<td>0.68–1.27</td>
<td></td>
</tr>
<tr>
<td>224–280</td>
<td>0.95</td>
<td>0.78–1.14</td>
<td></td>
</tr>
<tr>
<td>&gt;280</td>
<td>2.06*</td>
<td>1.50–2.82</td>
<td></td>
</tr>
<tr>
<td><strong>168–224</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N timing × form§</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall AA</td>
<td>0.53*</td>
<td>0.40–0.71</td>
<td></td>
</tr>
<tr>
<td>Sidedress AA</td>
<td>1.04</td>
<td>0.85–1.27</td>
<td></td>
</tr>
<tr>
<td>Spring AA</td>
<td>1.44*</td>
<td>1.00–2.09</td>
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</tr>
<tr>
<td>Spring UAN</td>
<td>0.92</td>
<td>0.64–1.32</td>
<td></td>
</tr>
<tr>
<td>Sidedress UAN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Previous crop in rotation</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Soybean</td>
<td>0.47*</td>
<td>0.37–0.61</td>
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<tr>
<td>Wheat</td>
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<td>0.27–0.60</td>
<td></td>
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<tr>
<td>Corn</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Tillage¶</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-till</td>
<td>0.58*</td>
<td>0.48–0.70</td>
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</tr>
<tr>
<td>Tilled</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Drainage class#</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Poorly</td>
<td>0.66*</td>
<td>0.55–0.80</td>
<td></td>
</tr>
<tr>
<td>Well</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N inhibitor††</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>1.09</td>
<td>0.79–1.49</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>March–August rainfall, cm</td>
<td>0.97+</td>
<td>0.94–1.00</td>
<td></td>
</tr>
<tr>
<td>SOM</td>
<td>1.00</td>
<td>0.99–1.02</td>
<td></td>
</tr>
</tbody>
</table>

† Three out of four CSNT values taken from three dominant soil types in each field are used for analysis. The fourth sample in each field is taken in the stressed area with yellow canopy color, which was only used for educational purpose to show the farmers how stress can affect CSNT.‡ Reference categories are underlined.§ Fall AA = anhydrous ammonium applied in fall; Sidedress AA = anhydrous ammonium applied as sidedress; Sidedress UAN = urea ammonium nitrate applied as sidedress; Spring AA = anhydrous ammonium applied in spring as pre-plant; Spring UAN = urea ammonium nitrate applied in spring.¶ Tilled = strip tillage and chisel tillage in spring and/or fall. No-Till = no tillage.** Poorly drained = including excessively drained, well drained, and moderately well drained soils; Poorly drained = including somewhat poorly drained, poorly drained, and very poorly drained soils.†† Yes = N inhibitor was applied with fertilizer N; No = N inhibitor was not applied with fertilizer N. N inhibitors used in the studied fields included Agrotain (by Koch Agronomic Services, LLC), a urease inhibitor applied with UAN; Instinct (by Dow AgroSciences), a nitrification inhibitor applied with UAN; and N-Serve (by Dow AgroSciences), a nitrification inhibitor applied with AA.
a dry spell, can also contribute to annual variations in N loss and availability (Cameron et al., 2013). Because year is a factor that includes the interaction of multiple variables, its usefulness for providing information to improve N recommendations is limited. This finding highlights, however, the large uncertainties in annual N availability that can be caused by factors other than the ones we measured.

**Growing Season Cumulative Rainfall**

An earlier 12-yr study (Balkcom et al., 2003) estimated that 74% of the year-to-year variation in mean pre-sidedress soil NO$_3^-$–N (samples were collected in the first 2 wk of June) and 62% of the year-to-year variation in mean CSNT values could be explained by spring rainfall (cumulative March through May). In our study, spring rainfall and growing season rainfall (cumulative March through August) varied across states and years (Fig. 4). We found that both spring rainfall and growing season rainfall significantly affected the cumulative probability of cornstalks to test in a higher CSNT category. However, the best-fit model included the growing season rainfall, suggesting that, in our study region, growing season rainfall is the stronger predictor of N availability during the growing season. Specifically, the higher the cumulative growing season rainfall, the lower the N availability to the corn crop (Table 3).

This reduced N availability can be explained by the substantial amount of N loss through leaching, runoff, and denitrification that occurs during wet seasons and periods of heavy rainfall. For example, studies have shown that NO$_3^-$ concentrations in rivers in the US Midwest tend to be greatest in spring and that annual mean concentrations tend to increase with increasing mean annual water flows into these rivers (Keeney and DeLuca, 1993; Lucey and Goolsby, 1993; Kalkhoff et al., 2000; Balkcom et al., 2003; Thorburn et al., 2013). In particular, Balkcom et al. (2003) found that spring water flows during March through May (influenced by spring rainfall) in the Iowa River at Wapello, IA, explained 91% of the variation in CSNT values. In Iowa, the ratio of spring to growing season rainfall is higher than in the more eastern parts of the Corn Belt where our current study was located. This difference may explain why we found growing season rainfall a stronger predictor of N availability compared with spring rainfall.

**N Application Rate**

In some cases, the N application rate had a significant effect on the cumulative probability for cornstalks to test in a higher CSNT category (Table 3). Cornstalk samples from fields with N application rates <112 kg ha$^{-1}$ were less likely (odds ratio = 0.66) to test in a higher CSNT category compared with samples from fields that received the most common rate of 168 to 224 kg ha$^{-1}$. This finding indicates that corn has a greater risk of experiencing insufficient N as indicated by CSNT when N rates are below 112 kg ha$^{-1}$. When CSNT is in the deficient category, the likelihood of insufficient N and yield loss is highest. When CSNT is in the marginal category, although the amount of yield loss is much smaller than when in the deficient category, the likelihood of insufficient N and yield loss is still high (Binford et al., 1990, 1992; Hooker and Morris, 1999; Fox et al., 2001). In contrast, samples from fields that received N application rates >280 kg ha$^{-1}$ were 2.06 times more likely to test in a higher CSNT category compared with fields that received the most common rate. This finding suggests that decreasing N application rates in fields that received >280 kg ha$^{-1}$ and tested in the excessive CSNT category would be a prudent recommendation. In such cases, reducing N rates could reduce both wasteful fertilizer expenditures and environmental risks caused by N loss. Notably, compared with the most commonly applied N rate of 168 to 224 kg ha$^{-1}$ (43% of samples), we found no significant differences in the chance to test in a higher category for samples from fields that received 112 to 168 kg ha$^{-1}$ (9% of samples) or 224 to 280 kg ha$^{-1}$ (35% of samples).

The Right rate is the component of the 4Rs that receives the most emphasis when farmers and environmentalists discuss ways to improve NUE. Our data suggest, however, that unless the N rate is <112 kg ha$^{-1}$ or >280 kg ha$^{-1}$, rate has little influence on...
the probability of a sample testing in a higher CSNT category. This finding indicates that N rate was a weak driver of N availability for 87% of the fields sampled, which suggests that improvements in N availability may be more dependent on the other three Rs: Right form, Right timing, and/or Right placement.

**N Application Form and Timing**

AA and UAN were the two predominant forms of N fertilizer used by the farmers in this study. When N form and timing data were pooled across all states and years, 67% of the fields received sidedress UAN or AA, 19% received fall AA, 8% received spring UAN, and 6% received spring AA (Table 2). When data were compared among states, 61% of the cornstalk samples from IL were fertilized with fall AA, whereas most samples from the states of IN, MI, and OH were fertilized with sidedress AA or UAN (Table 4).

A limited amount of research has focused on the effects of N form and timing on N availability for the crop or subsequent yield (Kyveryga et al., 2010). We found that a combination of N form and timing had a significant effect on CSNT and our results revealed the complexity of choosing the most efficient combination of the 4Rs (Table 3). Cornstalk samples from fields where fall AA was applied were 2.70 or 1.95 times less likely to test in a higher CSNT category compared with samples from fields with spring AA or sidedress AA applications, respectively. This result is consistent with our previous study conducted in Iowa that found spring-applied AA was more efficient than fall-applied AA (Kyveryga et al., 2010). In the current study, we also showed that samples from fields with spring-applied AA were 1.39 times more likely to test in a higher category compared with samples from fields with sidedress-applied AA. But, this difference was not statistically significant. Similarly, we found no significant difference in the odds of testing in a higher CSNT category between spring-applied UAN and sidedress-applied UAN. Additionally, our finding of no significant difference between fields that received sidedress AA or sidedress UAN indicated that N availability was similar between AA and UAN when applied as sidedress. However, samples from fields where UAN was applied as sidedress were 1.87 and 0.69 times more likely to test in a higher CSNT category compared with samples from fields with fall-applied AA and spring-applied AA, respectively.

Possible explanations for the greater potential of sidedress-UAN samples to test in a lower CSNT category compared with the spring-AA samples are many-fold. When AA is applied in the spring, ammonia (NH$_3$) is easily converted to ammonium (NH$_4^+$), but subsequent nitrification is inhibited by free NH$_3$ induced death of nitrifiers in the band where the AA application was concentrated (Ball-Coelho and Roy, 1999). Because NH$_4^+$ is a cation, it can be held on soil cation-exchange sites, thereby minimizing N loss from leaching (Havlin et al., 2005). In comparison, UAN has greater potential for leaching loss. The NO$_3^-$ portion of the UAN (25% of total N) is highly susceptible to leaching and denitrification loss, especially in wet springs (Sawyer, 2007). Also, the urea portion of the UAN (50% of total N) can volatilize when placed on the soil surface (Havlin et al., 2005) and urea is water soluble and prone to leaching loss. Furthermore, sidedress UAN can be positionally unavailable to the corn if applied at or near a dry soil surface and post-application rainfall is insufficient to move the N to the roots (Gardinier et al., 2013). Research has also shown that when applying AA, N uptake often increases relative to other N sources, particularly in dry growing seasons (Ball-Coelho and Roy, 1999).

Delaying N applications until the time of sidedressing is traditionally thought to be one of the most efficient ways to increase NUE (Anderson and Kyveryga, 2016). But, we found no significant difference in the likelihood of samples testing in a higher CSNT category when UAN was applied in the spring or as sidedress. Similarly, previous research has also reported that UAN application time (spring or sidedress) has no effect on grain yield and N loss (Stecker et al., 1993).

We found that fall AA significantly reduced the odds of cornstalk samples testing in a higher CSNT category compared with samples from fields that received sidedress or spring AA. This result agrees with previous studies that have shown that fall AA lowers NUE and corn yield (Vetsch and Randall, 2004). If AA is applied too early in the fall when soil temperatures are greater than 4°C, the NH$_3$ and NH$_4^+$ can be converted to NO$_3^-$ (Havlin et al., 2005). The NO$_3^-$ is then subject to leaching loss, which can be substantial with excessive spring rainfall (Anderson and Kyveryga, 2016), and to denitrification loss during freeze-and-thaw cycles during winter and early spring. Even if AA is applied when soil temperatures are low in the fall, the NH$_4$ and NH$_4^+$ can still be converted to NO$_3^-$ early in the spring, increasing the risks of denitrification and nitrate leaching when crop uptake is slow, but spring rainfall is high (Chalk et al., 1975; Vetsch and Randall, 2004).

Fall application of AA has several benefits, though, including a lower price for AA, greater labor availability, and typically favorable field conditions compared with the spring. Consequently, fall-applied AA can be a good form and timing choice under drier spring conditions. But, because spring weather is unpredictable, this practice can lead to large N losses in wetter springs. Therefore, estimating the rate of N to apply in the fall is difficult (Sawyer, 2007). The farms in IL accounted for 96% of fields that received fall AA (Table 4). To compensate for N losses and obtain optimum yields and economic returns, we recommend that farmers determine spring N fertilizer needs based on a spring soil test N or a pre-sidedress soil nitrate test.

More importantly, our findings indicate that the most efficient combination of N form and timing is spring-applied AA, which is consistent with our Iowa study results (Kyveryga et al., 2010). Changing the time of AA application from fall to spring
samples from tilled fields (Table 3). This result was also con-
in a higher CSNT category (odds ratio = 0.58), compared with
Tillage
Crop Rotation
Most states in the US recommend an N credit whenever soy-
bean is planted in rotation; therefore, the recommended N rate
is smaller for corn after soybean compared with corn after corn.
This practice is supported by many previous studies (Blackmer
et al., 1997; Gerwing and Gelderman, 2005; Shapiro et al.,
2008; Schoessow et al., 2010; Kaiser et al., 2011; Camberato
and Nielsen, 2017; Steinke, 2017) and by our Iowa study, where
we found that the mean recommended N rate was 45 to 56 kg
ha\(^{-1}\) smaller for corn after soybean compared with corn after
corn (Kyveryga et al., 2010). Similarly, in this multi-state study,
we found that fields with corn–corn rotations received a mean
N application rate of 236 kg ha\(^{-1}\) and fields with corn–soybean
rotations received 208 kg ha\(^{-1}\)—a reduction of 28 kg ha\(^{-1}\).

Yet, our current OLR analysis suggests that reducing N input
for corn after soybean compared with corn after corn may not be
the best practice. We found that crop rotation had a significant
effect on the cumulative probability of a cornstalk sample to
test in a higher CSNT category. When corn followed soybean
or wheat, the odds ratios were 0.47 and 0.40, respectively. That
is, holding all other variables constant, cornstalk samples had
a much lower likelihood of testing in higher CSNT categories
under corn–soybean or corn–wheat rotations compared with a
corn–corn rotation. These results are consistent with our Iowa
study (Kyveryga et al., 2010). Other research found no yield
benefit for corn between corn–soybean and corn–corn rotations
(Stanger and Lauer, 2008). Two reasons may account for our
finding. First, soybean production can result in a net removal of N
because export of N in soybean seeds can be greater than biologi-
cal fixation of N (Heichel and Barnes, 1984; Martens et al., 2016;
Schoessow et al., 2010). Second, farmers may have planted hybrids
with greater NUE in the corn–corn fields (Kyveryga et al., 2010).

Tillage
Cornstalk samples from no-till fields were less likely to test
in a higher CSNT category (odds ratio = 0.58), compared with
samples from tilled fields (Table 3). This result was also con-
sistent with our Iowa study (Kyveryga et al., 2010) and may be
due in part to the large amounts of corn residue left on fields
that grow corn for grain. In contrast to no-till systems, tillage
enhances corn residue mineralization by increasing aeration,
incorporating crop residues, and disrupting soil aggregates.
Mineralization of the organic N in the corn residue increases
N availability (Balesdent et al., 1990; Cambardella and Elliott,
1993) and may partially explain the overall higher CSNT values
for samples from tilled fields compared with no-till fields (Table
2). The significant difference may also be due to greater N loss
in wet years via greater infiltration from a greater number of
macropores in the soils of the no-till fields (Kanwar et al., 1997).

Additionally, no-till fields experience greater N immobilization
because soil surface residues typically have a high C to N ratio
(>20:1) (Kyveryga et al., 2010). However, the numerous envi-
ronmental, economic, and soil health benefits of no-till systems
likely outweigh the possibility of greater N availability with a
change to a tillage system (Karlen et al., 2013).

Soil Drainage Class
The use of soil drainage class for estimating N application
rates in precision agriculture has been controversial, even
though the degree of soil drainage can have a great effect on N
availability. For example, the practice of varying N rates based
on soil drainage class can have limited benefits because weather
can have a much larger effect on N availability (Sogbedji et
al., 2001; Van Es et al., 2005). In contrast, our Iowa study
(Kyveryga et al., 2010) found that drainage class had a signifi-
cant effect on N availability, based on CSNT values.

In this multi-state study, we also found a statistically signifi-
cant effect of drainage on N availability, based on CSNT values.
That is, cornstalk samples from poorly drained soils were much
less likely to have CSNT values in a higher category (odds ratio
= 0.66) compared with samples from well drained soils. Two
possible reasons for this finding are: (i) poorly drained soils
experience greater amounts of denitrification, especially in wet
years (Nash et al., 2012), and/or (ii) fields with poorly drained
soils can experience greater amounts of N leaching via tile
drains (Randall et al., 1997; Jaynes et al., 2001). Tile drain sys-
tems are routinely installed in our study’s fields that had poorly
drained soils, but we did not document this information.

N Inhibitor
The OLR models indicated no significant difference in the
odds ratio when samples from fields with and without N inhibi-
tor use were compared. This finding suggests that applying an N
inhibitor, regardless of N form and timing, does not affect the
odds of a cornstalk sample to test in a higher CSNT category.

Previous studies support the ability of N inhibitors to reduce
AA nitrification or UAN denitrification and, in turn, increase
yield (Kidwaro and Kephart, 1998; Zaman et al., 2009). Yet,
other studies have found that N inhibitor applications may not
increase corn yield or N uptake (Hatfield and Parkin, 2014).

Comprehensive information about N inhibitor effects on NUE
has been compiled on the NutrientStar website (http://nutrient-
star.org), which is supported by the Environmental Defense Fund.

Possible reasons for the non-response associated with N inhibitor
use in our study include: (i) farmers applied fall AA when soil
temperatures were below 5 to 6°C and nitrification was minimized
(Havlín et al., 2005); hence, the benefit of the N inhibitor with
fall AA was masked by low soil microbial activity; (ii) nitrification
potential was temporarily reduced by high rates of side-dressed
or spring AA, which served a similar function as N inhibitors (Ball-
Coelho and Roy, 1999); or, (iii) rainfall was insufficient for leach-
ing of nitrate during the time the inhibitor was protecting the N;
therefore, the inhibitor did not have an effect on corn N status.

CONCLUSIONS
We combined CSNT observations, digital soil maps, aerial
imagery of the corn canopy, and OLR modeling to identify
major factors that can significantly influence field-scale, corn
N status during the growing season. For an area that spanned multiple Corn Belt states, we quantified influential effects by calculating the odds ratio of CSNT N sufficiency levels, comparing different management options (e.g., fall AA vs. sidedress AA, tillage vs. no till, or corn-soybean vs. corn-corn rotations) and different environmental conditions (e.g., well drained vs. poorly drained soils or growing season rainfall). Results confirm the usefulness of our new data collection, analysis, and modeling methods, which can be applied to a broader corn production area or modified for a different cropping system. Based on the results from OLR modeling of 2760 CSNT samples collected from 920 fields between 2008 and 2014, we identified three types of factors that significantly influenced N sufficiency levels: (i) factors that farmers can change; (ii) factors that farmers cannot change, but can implement management practices to minimize their effects; and (iii) factors that farmers cannot predict, manage, or change.

The 4Rs of Nutrient Stewardship (IPNI, 2012) is an excellent framework for discussions about improving N management. But, farmers and farm advisors need data to make informed decisions about the complexity of factors that influence which combination of the 4Rs is most efficient for their farm fields. This research supports the concept of the 4Rs framework by quantifying N rate, form, and timing effects on N availability. Our data also provide farmers and farm advisors with new information about other important factors, not typically included in current N recommendations and management decision-making, that can significantly affect N availability. For example, we found that N application rate, which has been a primary focus of researchers and farmers for improving N efficiency and availability, should be considered within the context of other influential, field-scale management and environmental factors. These factors include N form and timing, tillage and crop rotation practices, soil drainage class, and cumulative growing season rainfall. We acknowledge that the large uncertainties in annual N availability can be caused by factors other than those we measured and highlight the need for continued research in this area.

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