UTILIZING HYDROLOGIC SOIL GROUPING TO ESTIMATE CORN NITROGEN RATE RECOMMENDATIONS

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By
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The undersigned, appointed by the dean of the Graduate School, have examined the dissertation entitled

UTILIZING HYDROLOGIC SOIL GROUPING TO ESTIMATE CORN NITROGEN RECOMMENDATIONS

Presented by G. Mac Bean,

A candidate for the degree of Doctor of Philosophy, Natural Resources, and hereby certify that, in their opinion, it is worthy of acceptance.

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DEDICATIONS

To

my beautiful and eternal companion

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First and foremost I give thanks to my loving Father in Heaven whose hand I recognize in all things, especially in providing opportunities for me to further my education. Interestingly, as I've strengthened my faith in Him my desire to learn has increased.

In high school, if someone would have told me I was going to spend the next 10+ years of my life going to classes and taking exams I would have laughed in their face. School never came naturally to me. I only narrowly passed the fourth grade, in high school I rarely opened a textbook outside the classroom and constantly formulated ridiculous plans with my knucklehead-buddies to skip class. I only applied to one college with absolutely no backup plan if I would have been rejected. Nonetheless, here I am years later completing a doctorate degree. Additionally, I recognize that I really can't take any of the credit. This achievement was only made possible through the tireless efforts of others, over many years, who are essential "co-authors" to my doctorate degree.

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DISSERTATION ABSTRACT

Nitrogen fertilizer recommendations in corn (*Zea mays* L.) that match crop N need are imperative to increasing profitability and preventing environmental contamination. However, processes influencing corn production (i.e. leaching and denitrification) are affected by soil and weather characteristics making it difficult to know when and how much N fertilizer to apply to match crop N need. In an effort to improve N fertilizer management, this dissertation explored the ability of soil, weather, and microbial respiration measurements to inform N rate recommendations based on hydrologic soil grouping (HG) and drainage classifications. Using 49 sites over three growing seasons (2014-2016), five HG-based groups were delineated. Following linear regression, soil and weather measurements were found related to the economical optimum N fertilizer rate (EONR) unique to each of the respective groups resulting in five separate N recommendation models. Furthermore, a total of 182 site-years of corn N response trial data were gathered across six U.S. Midwest Corn Belt states to validate these models. Two analyses were performed, one for comparing the HG-based model recommendations to EONR and another comparing HG-based model recommendations to state-specific corn N rate tools. Across all site-years and N timings the HG-based N recommendations were within 34 kg N ha^{-1} of EONR 38% of the time. State-specific N recommendation tools were within 34 kg N ha^{-1} of EONR 32% of the time. Over all site-years the HG-based models were more sensitive to site-specific crop N demand. In addition, when analyzed within each individual state, significant differences between approaches were observed. While

showing some promise, these results suggest more research is required to determine the applicability of the HG-based model approach for corn N fertilizer management.

Chapter 1: Literature Review

1.1 Abstract

Corn production across the U.S. Corn belt can be often limited by the loss of nitrogen (N) due to leaching, volatilization, and denitrification. In some fields, the use of N fertilizer recommendation tools for making in-season N fertilizer applications has been proven effective in matching plant N requirements with periods of rapid N uptake (V7-V11), reducing the amount of N lost to these processes. However, soil variability within fields, partnered with unpredictable weather make it difficult to estimate how much and when to apply N fertilizer to optimize crop uptake and minimize loss. Soil properties such as soil respiration and soil groupings such as the United States Department of Agriculture-Natural Resource Conservation Service's defined hydrologic groups have been related to N response. Several additional soil and weather properties such as soil texture, soil organic matter, total precipitation, and the distribution of precipitation have also been observed to effect the interaction between N and corn yield. Therefore, these interactions influence in-season N fertilizer recommendations. Objectives for this research were to 1) evaluate the ability of soil respiration to estimate crop N need for optimal grain production, 2) delineate sites by USDA-NRCS defined HG and drainage classification, 3) determine which soil and weather variables are best at estimating EONR in each delineated group mentioned in objective two, 4) use the results from objective three to develop HG-based N recommendation models, and 5) use independent corn N response

datasets to validate the developed N fertilizer recommendation models of objective 4.

1

1.2 Introduction

It should be noted that the following literature review is not meant to be comprehensive. Instead, each results chapter (chapters 2 – 4) includes an in-depth introduction and literature review specific to the topics of that unique chapter. This was done in preparation for scientific journal publication.

Nitrogen (N) is a plant essential nutrient and the fourth most abundant element in plants after oxygen, hydrogen, and carbon (Zeiger, 2010). Nitrogen is required for the construction and formation of critical plant processes and constituents, such as amino acids, proteins, nucleic acids, coenzymes, hormones, and chlorophyll. For cereal crop production, N is particularly important for obtaining optimal grain yield. This is especially true for supporting corn (Zea mays L.) production where it has been found to be most limited by the lack of N (Stanford, 1966; Stanford and Smith, 1971; Xie et al., 2013).

Producers often apply uniform amounts of N fertilizer over entire corn fields, usually before or at planting (Scharf and Lory, 2009). The spatial variability throughout any given field makes it difficult for uniform applications of N fertilizer to match the needs of every area in the field. The amount of N available in the soil at any particular location within a field is mainly determined by temperature, organic matter, and soil water content (Stanford and Smith, 1971), adding to the complexity of measuring the N supplying process of the soil and making N fertilizer recommendations that are site-specific. The amount of N applied in one part of the field could be adequate for some plants while being inadequate for others. Many studies have been conducted demonstrating that N need is highly variable within fields and justifies variable in-field N fertilizer applications (Mamo et al., 2003; Scharf et al., 2005; Shahandeh et al., 2011; Lambert et al., 2006). When uniformly applied, some field areas will have over-applied N and will result in excessive amounts of N fertilizer; the over-applied N leaches through the soil and pollutes the surface and ground water. In general, an estimated 50 to 70% of all N applied is lost (Hodge et al. 2000). Contrary to applying too much N, yield and profit loss occurs in areas that do not receive enough N. In recent decades efforts have been made to reduce the amount of N lost during corn production by improving N use efficiency (NUE; Morris et al., 2018; Raun et al., 1999).

Working to improve NUE helps ensure the N fertilizer applied is used by the plant and not lost to leaching, volatilization, denitrification, or surface runoff into streams and rivers. One of the best ways to accomplish this is by estimating or synchronizing the N fertilizer application or availability with the corn plant's ability to utilize it (Scharf and Lory, 2006). Research has found that the period of most rapid N uptake for corn is between the vegetative growth stages of V9 and V18.

In an attempt to estimate corn N need, N fertilizer recommendation tools have been developed and are currently being used by producers to help assist in N fertilizer applications (Morris et al., 2018). These tools include active-optical reflectance sensors, Maximum Return to Nitrogen tool (MRTN), Pre-plant and Pre-sidedress soil nitrate tests, and crop growth models. Dependent on year and location, these N recommendation tools have been somewhat successful in improving NUE (Raun et al., 1999; Williams et al., 2007; Kitchen et al., 2010; Scharf et al., 2011; Schmidt et al., 2009; Bean et al., 2018; Ransom et al., 2018; Morris et al., 2018). However, due to the soil variability among and within fields, coupled with unpredictable weather, tremendous uncertainty still exists for deciding how much and when to apply N fertilizer to reach optimal yield while not over-applying (Bean et al., 2018; Ransom et al., 2018).

1.3 Soil and Weather on Corn Nitrogen Response

Nitrogen fertilizer recommendations based on the interactions of soil and weather conditions are extremely limited (Tremblay, 2004). Yet, weather largely determines the biological activity in soil, which includes the decomposition of soil organic matter (Bolinder et al., 2007; van Es et al., 2007; Lokupitiya et al., 2010). Soil mineral N has been found to be affected by both precipitation and thermal units, which in turn ultimately affect corn's response to N (Tremblay, 2004; Tremblay and Belec, 2006; Shanahan et al., 2008; Kyveryga et al., 2007). In some soils, such as a Brookston clay soil (a fine-loamy, mixed, superactive, mesic Typic Argiaquoll), 80% of the variability seen in corn yields is a result of temperature and precipitation (Dirks and Bolton, 1981). As such, NUE is also largely affected by precipitation and temperature. A greater response to N fertilizer is generally seen during wet years than during dry years (Yamoah et al., 1998). Nitrogen response to added N across North America was found to be most affected by the precipitation during June and July as well as temperatures during July and August (Jeutong et al., 2000). Some have suggested that the distribution of rainfall is as equally important and should be considered when managing N (Shaw, 1964;

Reeves et al., 1993). For example, total rainfall for any given month of 15 cm spread out over six events over the month will have a vastly different impact on the soil and crop than one rainfall event totaling 15 cm. The Shannon Diversity Index (SDI) is one of many indices that has been used to quantify rainfall distribution. A SDI value of one would suggest a complete evenness of rainfall over a given period of time while a value of zero would suggest a complete unevenness of rainfall.

In arid climates, it was found that soils containing more clay return greater yields (Tremblay et al., 2011). However, in wet climates soils with a coarser texture result in greater yields. Therefore, a 51 site-year meta-analysis was performed by Tremblay et al. (2012) to determine N response of corn when compared to soil texture, total precipitation (PPT), corn heat units (CHU), SDI, and abundant and well-distributed rainfall (AWDR). Table 1.1 shows the equations needed to calculate PPT, CHU, SDI and AWDR (Tremblay et al., 2012). Research concluded soil texture was, to a large degree, the most influential factor in determining corn response to N. The average response to N fertilizer over the entire 51 sites for fine textured soils was greater than the average response for medium textured soils. Alone, CHU values only explained a small variation in N fertilizer response. In addition to soil texture, PPT, SDI, and AWDR significantly influenced the corn's response to N fertilizer.

1.4 Soil Respiration

Some soil properties are considered more or less static (e.g. soil texture). However, recent interest has been focused on more dynamic soil properties such as soil respiration. Tests for soil respiration, whether performed in lab or in-situ, measure soil microbial activity via the release of CO_2. Soil microbial activity is related to the active soil organic pool (Franzluebbers et al., 2000). This is often referred to as labile carbon. Labile carbon pools are crucial for determining the plant-available nutrient supply, soil structure, and the decomposition of both natural and synthetic compounds (Franzluebbers et al., 2000). Research has also found soil microbial activity to be related to net N mineralization and total N uptake by plants (Doran and Parkin, 1994, 1996; Marumoto et al., 1982; Sparling et al., 1995; Franzluebbers et al., 2000; Franzluebbers and Brock, 2007; Franzluebbers and Stuedeman, 2008; Franzluebbers and Haney, 2017; Franzluebbers et al., 2018; Franzluebbers and Pershing, 2018). Some have related soil respiration directly to the economic optimal N fertilizer rate (EONR) for corn production. As soil respiration increased, EONR decreased (Yost et al., 2018; Franzluebbers, 2018). This suggests corn fields that are responsive to added N fertilizer have lesser amounts of soil microbiological activity and require greater amounts of inorganic N. Additionally, sites unresponsive to applied N fertilizer are those receiving sufficient amounts of N made available through the soil microbial consortium (i.e., mineralization). Therefore, soil respiration coupled with other soil and weather information may be able to assist in estimating the amount of N fertilizer needed to match corn N need and thereby help protect the environment.

1.5 In-situ Soil Respiration Tests

In-field or “in-situ” respiration tests have been common for decades (Rochette and Hutchinson, 2005). These techniques have successfully related respiration to changes in soil management practices (Cabrera and Kissel, 1988a, b). While representative of natural conditions of fields, in-field respiration methods are labor intensive, may require refrigeration, and are affected by several uncontrolled or unmeasured factors, such as varying soil and air temperatures, CO_2 concentration gradients, pressure fluctuations, soil and air moisture, site disturbance, and chamber leakage.

With in-situ chamber methods, the design and deployment durations are affected by soil temperature differences between the inside and outside of the chamber. Temperature changes can vary by $+5^{o}C$ to $-18^{o}C$ (Sharkov, 1984; Matthias et al., 1980), and every $1^{o}C$ change in soil temperature results in about 7% respiration rate change (Rochette and Hutchinson, 2005). With soil temperatures in constant flux throughout the growing season, day, and across the field, comparing soil respiration samples across time and space becomes difficult. This problem is magnified as treatments and replications increase, increasing the total samples, and therefore time required, per sampling event. From the time the first sample is taken to the time the last sample is taken, the soil temperature has almost certainly changed. Furthermore, fluctuating air temperatures alter chamber pressure. As air temperatures rise, chamber pressure increases. This relationship acts as a piston pushing and pulling the air out of the soil beneath. While this problem is solved with vented chambers, if chamber and ambient CO_2 concentrations differ, chamber leakage occurs (Rochette and Hutchinson, 2005). The extent of all these conditions vary between chambers and chamber locations ultimately introducing error and uncertainty into the accuracy of the soil respiration results.

In-situ soil samples that are collected from the field and then transported back to the lab for further analysis have several perceived shortcomings. These samples often require refrigeration or immediate handling, requiring the determination of initial soil water content for each soil sample, and have potential seasonal complications when the soil is too dry or wet (Rochette and Hutchinson, 2005; Franzluebbers, 1999).

1.6 Laboratory Soil Respiration Tests

Multiple laboratory respiration methods have been developed that are intended to approximate in-field conditions (Weil et al., 2003; Islam and Weil, 1998; Blair et al., 1995; van de Werf and Verstrate, 1987; Walkley and Black, 1947; Walkley and Black, 1934). These methods are adaptable and have been related to soil microbial biomass carbon and N mineralization, and are sensitive to changing management practices (Franzluebbers, 1999). These methods require the use of disturbed soil. Disturbance arises from samples being dried, sieved, and the use of standard protocols of re-wetting and incubating at constant temperatures to reduce the probability of introducing error into the respiration results. These samples are sealed in a chamber and incubated for a specified period of time. During incubation CO_2 is captured or trapped (Sherrod et al., 2012), then measured following the prescribed incubation time (Franzluebbers and Haney, 2017). The strength of laboratory respiration methods is they allow for averaging across spatial soil variability, flexibility in initial processing (no refrigeration), control over soil and air temperatures, maintaining standardized moisture content, and avoiding potential seasonal complications with sampling (Franzluebbers, 1999). Typically, laboratory mineralization methods are much more cost effective because of time efficiency (Sherrod et al., 2012). Differing techniques are used to rewet and measure the CO_2 and will be discussed in further detail later.

Investigations have also highlighted deficiencies of laboratory respiration methods. The required sieving of each soil sample releases labile-C that was otherwise protected by soil aggregates. This sample homogenization is found to cause a flush of CO_2 that may not have been observed with in-situ samples (Powlson, 1980; Elliott, 1986; Beare et al., 1994; Franzluebbers, 1999).Therefore, the determination of soil respiration using these methods may be biased (Crasswell and Waring, 1972; Merckx et al., 1985; Franzluebbers, 1999) Laboratory methods that use Mason jars can fail due to leaking jar lids and seals requiring multiple sample replicates. This method also produces chemicals that eventually need to be disposed of (Sherrod et al., 2012).

Measured water-filled pore space and capillary draw are two techniques that are used for rewetting laboratory respiration soil samples (Franzluebbers, 1999; Haney and Haney, 2010). Ultimately, it was found that either method could be used to accurately determine CO_2 soil respiration (Franzluebbers and Haney, 2017). However, each method has advantages and disadvantages. Allowing the soil sample to draw a known volume of water (usually 20 to 30 ml) through capillary forces preserves the porosity of the soil. Although, coarse textured soils have limited capillary strength preventing water infiltration and respiration. Additionally, in some soils the fixed amount of water applied results in >60% water filled pore space ultimately decreasing respiration. Contrastingly, the determination of water-filled pore space is not limited by soil texture. However, calculating the same water-filled pore space for every sample takes time and is an extra step to the sampling protocol.

1.7 Classifying Soils

Nitrogen is a reactive element sensitive to both soil and weather conditions, making it difficult to know how much soil N is available to the crop at any one specific moment. Soil texture, precipitation amount and distribution, and their effect on one another, have an important impact on corn's response to N fertilizer (Tremblay et al., 2012). Clayey soils can have a positive or negative effect on yield, based on the precipitation amount and distribution throughout the growing season (Shahandeh et al., 2011). For example, on a 64 ha field in Texas, corn yield was higher during dry years on clayey soils due to greater water-holding capacity while in wet years, yield was lower due to N loss via denitrification (Shahandeh et al., 2011). These results are similar to those found by many others (Schepers et al., 2004; Kravchenko and Bullock, 2000; Armstrong et al., 2009; Tremblay et al., 2011). Soil characteristics are varied through weather, and could be used to distinguish different management zones. Elements of this interplay between soil and weather has been captured by the United States Department of Agriculture's (USDA-NRCS) Soil Survey Geographic database (SSURGO). This database includes the depth to a restrictive layer or water table, the transmission rate of water, water holding capacity as a function of soil texture, soil structure, and the degree of soil swelling when saturated to define certain Hydrologic Soil Groups (HG; Table 1.2; NRCS 2009). Locations that fall within a specific HG are thought to respond similarly. Additionally, through the USDA and based on the frequency and duration of wet periods, seven defined classes of drainage have been established (Table 1.3; Soil Survey Division Staff, 1993). When considering NO_3-N loss on a watershed scale, HG were found to be one of the most important factors in estimating NO_3-N movement and loss pathways (Blanchard and Lerch, 2000). In the forested soils of southern Quebec, drainage class was significantly related to N transformation rates and internal N cycling (Ullah and Moore, 2009). Therefore, grouping field or site locations by this information may aid in determining, for locations within each group, the spatial and temporal variables most sensitive to understanding general processes governing N behavior in the soil and crop system.

Given this background, there are three needs proposed with this dissertation research. The first is to better understand the relationship between soil respiration and its ability to estimate the economical optimal N rate in corn production across the U.S. Corn Belt. Second, develop N recommendation models using soil and weather variables most related to EONR in specific USDA-ARS defined soil hydrologic groups and drainage class delineations. And third, validate the above approach outcomes using independent corn N fertilizer response datasets.

1.8 Objectives

The purpose of this research is to:

1. Evaluate the relationship between soil respiration and EONR.
2. Determine by HG and drainage class which soil, weather, or canopy reflectance information are best related to EONR.
3. Use the results from objective two to develop HG-based N recommendation models.
4. Use additional N response datasets to provide independent validation of the above mentioned (objective 3) N fertilizer recommendation models.

1.9 Bibliography

Armstrong, R.D., J. Fitzpatrick, M.A. Rab, M. Abuzar, P.D. Fisher, and G.J. O'Leary. 2009. Advances in precision agriculture in south-eastern Australia: III. Interactions between soil prperties and water use help explain spatial variabity of crop production in the Victorian mallee. Crop Pasture Sci. 60:870-884. doi:10.1071/CP08349

Bean, G.M., N.R. Kitchen, J.J Camberato, R.B. Ferguson, F.G. Fernandez, D.W. Franzen, C.A.M. Laboski, E.D. Nafziger, J.E. Sawyer, P.C. Scharf, J. Schepers, and J.S. Shanahan. 2018. Improving an active-optical reflectance sensor algorithm using soil and weather information. Agron. J…..

Beare, M.H., M.L. Cabrera, P.F. Hendrix, and D.C Coleman. 1994. Aggregate-protected and unprotected organic matter poolsin convential and no-tillage soils. Soil Sci. Soc. of Am. J. 58, 787-795

Blair, G.J., R.D.B Lefroy, and L. Lise. 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. Australian J. Agric. Res. 46:1459-1466.

Blanchard, P.E. and R.N. Lerch. 2000. Watershed vulnerability ot losses of agriucltural chemicals: Interactions of chemistry, hydrology, and land-use. Environ. Sci. Technol. 34(16) pp 3315-3322. doi:10.1021/es991115+

Bolinder, M.A., O. Andren, T. Katterer, R. de Jong, A.J. VandenBygaart, D.A. Angers, et al. 2007. Soil carbon dynamics in Canadian agriculural ecoregions: Quantifying climatic infuence on soil biological activity. Agric. Escsyst. Environ. 122.461-470. doi:10.1016/j.agee.2007.03.001

Cabrera, M.L., Kissel, D.E., 1988a. Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. Soil Sci. Soc. Am. J. 52:1027-1031

Cabrera, M.L., Kissel, D.E., 1988b. Potentially mineralizable nitrogen in disturbed and undisturbed soil samples. Soil Sci. Soc. Am. J. 52:1010-1015

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

Dirks D.A., and E.F. Bolton. 1981. Climatic factors contributing to year to year varation in grain yield of corn on brookston clay. Can J. Plant Sci. 61: 1918-1833. doi: 10.4141/cjps81-042

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J., et al. (Eds.), Defining Soil Qualtiy for a sustainable Environment. Soil Sci. Soc. Am. Spec. Publ. 35, Madison, WI, pp. 3-21.

Doran, J.W., Parkin, T.B., 1996. Quantitative indicators of soil quality: a minimum data set. In: Doran, J.W. Jones, A.J. (Eds.), Methods forAssessing Soil Quality. Soil. Sci. Soc. Am. Spec. Publ. 49, Madison, WI, pp. 25-37.

Elliott, E.T. 1986. Aggregate structure and carbon, nitrogen and phosphorus in native and cultivated soils. Soil Sci. Soc. Of Am. J. 50, 627-633

Franzluebbers, A.J. 1999. Potential C and N mineralization and microbial biomass from intat and increasingly disturbed soils of varying texture. Soil Biol. Biochem. 31:1083-1090.

Franzluebbers, A.J., R.L. Haney, C.W. Honeycutt, H.H. Schomberg, and F.M. Hons. 2000. Flush of caron dioxide following rewetting of dried soil relates to active organic pools. Soil Sci. Soc. Am. J. 64:613-623

Franzluebbers, A.J., and B.G. Brock. 2007. Surface soil responses to silage cropping intensity on a Typic Kanhapludult in the piedmont of North Carolina. Soil Tillage Res. 93:126-137. doi:10.1016/j.still.2006.03.021

Franzluebbers, A.J., and J.A. Steudemann. 2008. Early response of soil organic fractions to tillage and integrated crop-livestock production. Soil Sci. Soc. Am. J. 72:613-625. doi:10.2136/sssaj2007.0121

Franzluebbers, A.J., and R.L. Haney. 2017. Evaluation of soil processing conditions on mineralizable C and N across a textural gradient. Soil Sci. Soc. Am. J. doi:10.2136/sssaj2017.08.0275

Franzluebbers, A.J. and M.R. Pershing. 2018. Soil-test bilogical activity with the flush of CO_2: II. Greenhouse growth bioassay from soils in corn production. Soil Sci. Soc. Am. J. doi:10.2136/sssj2018.01.0024

Franzluebbers, A.J. 2018. Soil-test bilogical activity with the flush of CO_2: III. Corn yield responses to applied nitrogen. Soil Sci. Soc. Am. J. 82:708-721. doi:10.2136/sssaj2018.01.0029

Haney, R.L., and E.B. Haney. 2010. Simple and rapid laboratory method for rewetting dry soil for incubations. Commun. Soil Sci. Plant Anal. 41:1493-1501. doi:10.1080/00103624.2010.482171

Hodge A., D. Robinson, and A. Fitter. 2000. Are microorganisms more effective than plants at competing for nitrogen? *Trends in Plant Science*. 5: 304-308. doi: 10.1016/S1360-1385(00)01656-3

Islam, K.R. and R.R. Weil. 1998. Microwave irradiation of soil for routine measurement of microbial biomass carbon. Biol. and Fert. Soils 27:408-416.

Jeutong, F., K.M. Eskridge, W.J. Waltman, and O.S. Smith. 2000. Comparison of bioclimatic indices for prediction of maize yields. Crop Sci. 40: 1612-1617

Kitchen, N.R., K.A. Sudduth, S.T. Drummond, P.C. Scharf, H.L. Palm, D.F. Roberts, and E.D. Vories. 2010. Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. Agron. J. 102:71-84. doi:10.2134/agronj2009.0114

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. Agron. J. 92:75-83

Kyveryga P.M., A.M. Blackmer, and F. Morris. 2007. Alternative benchmarks for economically optimum rates of nitrogen fertilization for corn. Agron. J. 99:1057-1065. doi: 10.2134/agronj2006.0340

Lambert, D.M., J. Lowenberg-Doer, and G.L. Malzer. 2006. Economic analysis of spatial-temporal patterns in corn and soybean response to nitrogen and phsophorus. Agron J. 98:48-54.

Lokupitiya, E., K. Paustian, M. Easter, S. Williams, O. Andren, and T. Katterer. 2010. Carbon balances in US croplands during the last two decades of the twentieth century. Biogeochemestry 107:207-225. doi:10.1007/s10533-010-9546-y

Mamo, M., G.L. Malzer, D.J. Mulla, D.R. Huggins, and J. Strock. 2003. Spatial and temporal variation in economically optimum nitrogen rate for corn. Agron. J. 95:958-964

Marumoto. T., J.P.E. Anderson, and K.H. Domsch. 1982. Mineralization of nutrients from soil microbial biomass. Soil Biol. Biochem. 14:469-475

Matthias, A.D., A.M. Blackmer, and J.M. Bremner. 1980. A simple chamber technique for field measurement of emissions of nitrous oxide from soils. J. Environ. Qual. 9:251-256

Merckx, R., A. den Hartog, and J.A. van Veen. 1985. Turnover of root-derived material and related microbial biomass formation in soils of different texture. Soil Bio. and Biochem. 17, 565-569

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

Powlson, D.S., 1980. The effects of grinding on microbial and nonmicrobial organic matter in soil. J. Soil Sci. 31, 77-85.

Ransom, C.J., N.R. Kitchen, S. Anderson, P. Motavalli, D.B. Myers, P.C. Scharf, and J.S. Shanahan. 2018. Evaluting and improving corn N recommendation tools across the U.S. Midewest. Agron J. In review.

Raun, B.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 1999. Improving Nitrogen Use Efficiency in Cereal Grain Production with Optical Sensing and Variable Rate Application. Agron. J. 94:815-820

Roberts, D.F., R.B. Ferguson, N.R. Kitchen, V.I. Adamchuk, and J.F. Shanahan. 2012. Relationships between soil-based management zones and canopy sensing for corn nitrogen management. Agron J. 104:119-129. doi:10.2134/agronj2011.0044

Reeves, D.W., C.W. Wood, and J.T. Touchton. 1993. Timing nitrogen applications for corn in a winter legume conservation-tillage system. Agron. J. 85:98-106

Rochette, P and G.L. Hutchinson. 2005. Measurment of soil respiration in situ: chamber techniques. UNLincoln. Amer. Soc. Agron. Micrometeorology in Agricultural Systems, Agronomy monograph no. 47.

Scharf, P.C., Kitchen, K.A. Sudduth and J.G. Davis, V.C. Hubbard, and J.A. Lory. 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. Agron J. 97:452-461. doi:10.2134/agronj2005.0452

Scharf, P.C., and J.A. Lory. 2006. Best management practices for nitrogen fertilizer in missouri." *Integrated Pest Management*, 2006: 3-11.

Scharf, P.C. and J.A. Lory. 2009. Calibrating reflectance measurements to predict optimal sidedress nitrogen rate for corn. Agron. J. 101:615-625. doi:10.2134/agronj2008.0111

Scharf P. C., D. K. Shannon, H. L. Palm, K. A. Sudduth, S. T. Drummond, N. R. Kitchen, L. J. Mueller, V. C. Hubbard, L. F. Oliveira. 2011. Sensor-based nitrogen application out-performed producer-chosen rates for corn in on-farm demonstrations. Agron. J. 103: 1683-1691. doi:10.2134/agronj2011.0164

Schepers, A.R., J.F. Shanahan, M.A. Liebig, J.S. Schepers, S.H. Johnson, and A. Luchiari. 2004. Appointments of management zones for characterizing spatial varialbity of sil properties and irrigated corn yield across years. Agron. J. 96: 195-203

Schmidt, J,.P., A.E. Dellinger, and D.B. Beegel. 2009. Nitrogen recommendations for corn: An on-the-go sensor compared with current recommendation methods. Agron. J. 101:916-924. doi:10.2134/agronj/2008.0231x

Shahandeh H., A.L. Wright, and F.M. Hons. 2011. Use of soil nitrogen parameters and texture for spatially-variable nitrogen fertilization. Precis. Agric. 12: 146-163. doi:10.1007/s11119-010-9163-8

Sharkov, I.N. 1984. Determination of the rate of soil CO_2 production by the absorption method. Sov. Soil Sci. 16:102-111

Shaw, L.H. 1964. The effect of wether on agricultural output: A look at the methodology. J. Farm Econ. 46:218-230

Sherrod, L.A., J.D. Reeder, W. Hunter, and L.R. Ahuja. 2012. Rapid and cost-effectie method for soil carbon minearlization in static laboratory incubations. Comm. Soil Sci. and Plant Analysis. 43:6 958-972. doi:10.1080/00103624.2012.653031

Sparling, G.P., D.V. Murphy, R.B. Thompson, and I.R.P. Fillery. 1995. Short-term net N mineralization from plant residues and gross and net N mineralisation from soil organic matter after rewetting of seasonally dry soil. Aust. J. Soil Res. 33:961-973.

Stanford, G. 1966. Nitrogen requirements of crops for maximum yield. In: M.H. McVickar et al., editors, Agricultural anhydrous ammonia-technology and use. SSSA, Madison, WI,. p.237-257. https://dl.sciencessocieties.org/publications/books/tocs/acsesspublicati/agriculturalanh doi:10.2134/1966.nh3agricultural.c14

Stanford G., and S.J. Smith. 1971. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. J. 36:465-472. doi:10.2136/sssaj1972.03615995003600030029x

Tremblay, N. 2004. Determining nitrogen requirements from crops characteristics. Benefits and challenges, pg 157-182. In: S.G. Pandalai. Recent research developments in agronomy and horticulture. Res. Signpost, Kerala, India

Tremblay, N. and C. Belec. 2006. Adapting nitrogen fertilization to unpredictable seasonal conditions with the least impact on the environment. HortTechnology vol: 16 no: 3. Pg 408-412

Tremblay, N., M.Y. Bouroubi, P. Vigneault, and C. Bélec. 2011. Guidelines for in-season nitrogen application for maize (Zea mays L.) based on soil and terrain properties. Field Crops Res. 122:273–283. doi:10.1016/j.fcr.2011.04.008

Tremblay N., Y. M. Bouroubi, C, Belec, R. W. Mullen, N. R. Kitchen, W. E. Thomason, S. Ebelhar, D. B. Mengel, W. R. Raun, D. D. Francis, E. D. Vories, and I. O. Monasterio. 2012. Corn response to nitrogen is influenced by soil texture and weather. Agron. J. 104:1658-1671. doi: 10.2134/agronj2012.0184

Ullah, S. and T.R. Moore. 2009. Soil drainage and vegetation controls of nitrogen transformation rates in forest soils, southern Quebec. J. Geophys. Res. Biogen. doi:10.1029/2008jg000824

Van de Werf, H., and W. Verstrate. 1987. Estimation of active soil microbial biomass by mathematical analysis of respiration curves: Calibration of the test procedure. Soil Biol. and Biochem. 19:261-266.

van Es, H.M., B.D. Kay, J.J. Melkonian, and J.M. Sogbedji. 2007. Nitrogen managmenet for maize in humid regions: Case for a dynamic modeling approach. In: T.W. Bruulsems, editor, Managing Crop Nitrgoen for Wqeather: Proceedings of the Symposium "Integration Weather Variability inot Nitrgoen Recommendations," Indianapolis, IN. 15 Nov. 2006. Int. Plant Nutr. Inst. Norcross, GA. P.6-13

Walkley, A., and I.A. Black. 1934. An examination of the Degtjareff method for determing soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37:29-38

Walkley, A., and I.A. Black. 1947. Determination of organic matter in the soil by chromic acid digestion. Soil Sci. 63:251-264.

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, S.E. Samson-Liebig. 2003 Estimating active carbon for soil quality assessment: a simplified method for laboratory and field use. Am. J. Alternative Agriculture. Vol. 18, No. 1. doi: 10.1079/AJAA2003003

Xie, M., N. Tremblay, G. Tremblay, G. Bourgeois, M. Y. Bouroubi, and Z. Wei. 2013. Weather effects on corn response to in-season nitrogen rates. Can. J. Plant Sci, 2013: 407-417. doi: 10.4141/CJPS2012-145

Yamoah C.F., G.E. Varvel, C. Francis, and W. Waltman. 1998. Weather and management impact on crop yield variability in rotations. J. Prod. Agric. 11: 219-225. doi: 10.2134/jpa1998.0219

Zeiger, E., L. Taiz. 2010 Plant Physiology. 5th ed. Sinauer Associates Publ., Sunderland, MA.

1.10 Tables

Table 1.1. Equations used to calculate each weather variable described in Tremblay et al., 2012.

Weather Variable	Equation
Sum of the total rainfall (PPT)	Sum of the daily rainfall.
Corn heat units (CHU)	∑(Ymax + Ymin)/2; Ymax and Ymin are the daily maximum and minimum temperatures.
Shannon diversity index (SDI)	[-∑pi ln(pi)]/ln(n); pi = Rain/PPT (daily rainfall relative to total rainfall in a given time; n = number of days.
Abundant and well-distributed rainfall (AWDR)	PPT X SDI

Table 1.2. United States Department of Agriculture-Natural Resource Conservation Service's defined hydrologic soil groups (HG). The HG 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 an HG, the least transmissive layer is used.

Hydrologic group	Runoff	Water transmission	Soil texture	K_{SAT}	Depth to water table	Depth to impermeable layer
				cm hr^{-1}	----------cm----------	
A	Low	Unrestricted	>90% sand and <10% clay	>14.5	>61	>51
B	Mod. Low	Unrestricted	10-20% clay and 50-90% sand	3.6-14.5	>61	>51
C	Mod. 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 1.3. Descriptions of the United States Department of Agriculture's drainage classifications. Seven classes of natural drainage have been defined and refer to the frequency and duration of wet periods similar to those in which the soil formed. It should be noted that human modifications to drainage or irrigation were not considered in these classifications unless they greatly influenced the morphology of the soil.

Drainage Class	USDA Description
Excessively drained	• Water removed rapidly • Internal free water is very rare or deep • Coarse-textured soils with very high K_{SAT}
Somewhat excessively drained	• Water removed rapidly • Internal free water is rare or deep • Coarse-textured soils with high K_{SAT}
Well drained	• Water removed readily but not rapidly • Internal free water is deep to very deep • Water is available to plants for most of the growing season • Wetness does not prevent growth of roots for prolonged periods • Mainly free from redoximorphic features
Moderately well drained	• Water is removed from the soil somewhat slowly • Internal free water is moderately deep and transitory • Soils are wet within the rooting zone for only a short time during the growing season but long enough for mesophytic plants to be affected • Periodically receive high rainfall • Low K_{SAT} within the upper 1 m of soil • Periodically receives high rainfall
Somewhat poorly drained	• Water is removed slowly • Soil is wet at shallow depths for a significant amount of time • Internal free water is shallow to moderately deep and transitory to permanent • Wetness restricts the growth of mesophytic plants • Usually have either low to very low K_{SAT}, a high water table, continuous rainfall, or additional water seepage
Poorly drained	• Water is removed slowly • Soil is wet at shallow depths periodically or remains wet • Internal free water is shallow or very shallow and common • Free water is found at or near the surface for long periods of time • Mesophytic plants cannot be grown unless artificially drained • The soil is not continuously wet below the plow layer

Very poorly drained	• Shallow water table is a result of low K_{SAT} or continuous rainfall • Water is removed very slowly • Standing water for much of the growing season • Internal free water is very shallow and is persistent or permanent • Most mesophytic plants cannot be grown unless artificially drained • Soils are level or depressed and frequently have standing water

Chapter 2: Relating Four-day Soil Respiration to Corn Nitrogen Fertilizer Needs Across 49 US Midwest Fields

2.1 Abstract

Soil microbes drive biological processes that further mediate chemical and physical processes necessary for plants to sustain growth, including the decomposition of organic matter, the release of plant available nutrients, and the manipulation of soil structure. Soil respiration has been proposed as one universal indicator capable of measuring these functions. Soil respiration samples are typically taken prior to planting crops and analyzed within several weeks to potentially inform decisions for the coming growing season. Research is needed to support the premise that soil respiration is helpful for sustainable N management decisions in corn (*Zea Mays* L). Therefore the objective of this research was to relate soil respiration to at-planting and in-season N fertilizer applications for determining the economical optimal N fertilizer rate (EONR). A total of 49 N response trials were conducted across eight states over three growing seasons (2014 – 2016). The 4-day Comprehensive Assessment of Soil Health (CASH) soil respiration method was used to quantify soil respiration. When examined over all sites, N fertilization did not impact soil respiration. However, at four sites, as N fertilization at-planting increased soil respiration decreased. Across all years and sites soil respiration was moderately related to EONR ($r^2 = 0.20$). When analyzed by year, soil respiration was strongly related to EONR for 2016 ($r^2 = 0.50$), but much less for the first two years ($r^2 < 0.20$). These results illustrate the wide range of outcomes in soil respiration as

influenced by growing-season weather, and the problematic nature of its use as a universal indicator of corn N fertilization.

2.2 Introduction

Traditional N soil fertility research has been based on determining the amount of inorganic N fertilizer needed to maximize yield (Russell, 1963; Triplett et al., 1979; Jokela and Randall, 1989; Stecker et al., 1995; Shapiro and Wortman, 2006; Franzluebbers, 2018). Now, with increasing financial and environmental pressures, greater focus has been given to recommendations that align with the economical optimum N rate (EONR; Vanotti and Bundy, 1994; Scharf et al., 2005; Williams et al., 2007; Franzluebbers, 2018). However, spatial and temporal variability found in and among fields from one year to the next make determining EONR difficult. Various tools for predicting crop N fertilizer needs utilizing tests to approximate mineralization have been explored; examples include the anaerobic potentially mineralizable N (PMN; Stanford and Smith, 1972) test, Illinois Soil N (ISNT; Williams et al., 2007; Morris et al., 2018) test, soil microbial biomass (chloroform fumigation; Brookes et al., 1985), and NH_4-N by oxidative release (Stanford and Smith, 1978). Varying success has been documented using these approaches (Gagnon et al., 2001; Williams et al., 2007; Griffin, 2008; Morris et al., 2018).

The idea of measuring or estimating the amount of N that likely will be mineralized during the growing season has great appeal since it is one of the major factors causing spatial and temporal variability in corn yield. From such, a number of laboratory N mineralization tests have been evaluated with varying results (Griffin, 2008; Sherrod et al., 2017). Some have found laboratory PMN test results differ from actual field-measured mineralizable N amounts (Cabrera and Kissel, 1998; Rasmussen et al., 1998; Delphin, 2000). These differences can be attributed to variations in soil temperature, moisture, and immobilization from soil microbes (Wang et al., 2001). Additionally, the PMN test is costly and may require long incubation times (Idowu et al., 2008). The ISNT measures amino-sugar N concentration and reportedly successfully distinguished between N-responsive and non-responsive Illinois fields (Mulvaney et al., 2006). In contrast, ISNT was inversely related to EONR in North Carolina where fields were delineated by drainage class (Williams et al., 2007). In other North Carolina studies EONR varied by as much as 80 kg N ha^{-1} with but slight variation in ISNT values, demonstrating a lack of sensitivity to crop N need (Wall et al., 2010). Others studies have also found a poor relationship of ISNT with N responsiveness, and therefore only weakly related to EONR (Barker et al., 2006; Laboski et al., 2008; Osterhaus et al., 2008). Through chloroform fumigation extraction, measured soil microbial biomass explained 92% of the variance in N mineralization potential for 37 different soils (Brookes et al., 1985). However, others found weak relationships between soil microbial biomass and N mineralization potential (Groot and Houba, 1995; Hassink, 1994; Franzluebbers et al., 2001). Likewise, the relationship between NH_4-N measured by oxidative release and mineralizable N has been variable across studies. A strong relationship between NH_4-N and N mineralization was found in 39 different soils ($r^2 = 0.92$; Stanford and Smith, 1978) but Hadas et al. (1986) found a weak relationship between NH_4-N and N mineralization.

Other incubation tests estimate N need through measuring soil organic C. Soil organic C can be divided into labile and recalcitrant portions, with the latter being relatively stable in soils (Weil et al., 2003; Singh et al., 2018). Labile substances are water soluble and quickly decomposed by the microbial community (Singh et al., 2018; Ghani et al., 2003). These substances are made up of plant amino acids, microbial enzymes, and other plant residues which are decomposed easily by soil microorganisms with the mineral constituents made available for plant uptake and growth (Weil and Brady, 2015; Soil Science Society of America 1997; Lehmann and Kleber, 2015). Some have found labile-C measurements to be sensitive to changes in management practices, environmental variations, and soil productivity (Weil et al., 2003; Culman et al., 2012). Measuring labile-C and therefore the level of microbial activity could aid in crop N management decisions.

Under controlled conditions and without the addition of new C inputs, biological laboratory methods empirically separate labile-C from stabilized-C by allowing soil microbes to mineralize soil organic carbon (Mclauchlan and Hobbie, 2004). Microbes are presumed to mineralize labile-C first. Microbial activity can be observed by measuring the CO_2 produced during a set incubation period (Alvarez and Alvarez, 2000; Pastor et al., 1993). Although soil samples taken prior to planting or N fertilization are commonly used for analysis, few studies have documented the effect of sample storage on soil respiration. Generally, C respiration methods are adaptable (Lee et al., 2007). These methods have been related to soil microbial biomass carbon, N mineralization, and varying management practices (Franzluebbers, 1999; Franzluebbers and Haney, 2017).

This allows for averaging across spatial variability, flexibility in initial processing (no refrigeration), control over soil and air temperatures, moisture content, and avoids potential seasonal complications with sampling (Franzluebbers, 1999). Therefore, measuring and understanding labile-C as a metric of soil microbial activity and its influence on soil nutrient availability could ultimately assist with optimizing N fertilizer management.

Added N fertilizer has shown to have contradictory effects on soil respiration. Some observed added N fertilizer increased soil respiration through stimulation of soil microbes (Liljeroth et al., 1990; Pregitzer et al., 2000; Burton et al., 2002; Bowden et al., 2004). Others found as N fertilizer rates increased soil organic matter decomposition slowed and hindered soil respiration ultimately increasing total soil organic matter (Aber et al., 1993; Cao and Woodward, 1998). Thus the specific controls on C respiration relative to N availability and crop N need are not well understood.

The Haney Test, also known as the Soil Health Nutrient Tool, incorporates a 24 hr CO_2 “flush” or “burst” test (i.e. Solvita CO_2-Burst), water extraction of N and organic C, and the weak acid extraction of inorganic N (Yost et al., 2018; Franzluebbers et al., 1996; Doran et al., 1997; Haney and Haney, 2010; Haney et al., 2012; Haney et al., 2015). Using these measurements, soil health and plant available N calculations have been proposed and used to calculate N fertilizer rates for high-N demanding crops including corn (Yost et al., 2018). When compared to traditional grower N fertilizer rates in Texas, the Haney Test was found to recommend less N while maintaining profit (Harmel and Haney, 2016). However, when compared to the economically optimal N rate (EONR) in corn across 17 U.S. Midwest Corn Belt sites, the Haney Test did not perform as well (r^2 = 0.24; Yost et al., 2018). Interestingly, the 24-hr Solvita CO_2-Burst test portion of the Haney test was found related to EONR (r^2 = 0.61; Yost et al., 2018). In another study considering 47 corn N response trials across North Carolina and Virginia, measured soil respiration was also found related to EONR (r^2 = 0.45; Franzluebbers, 2018). On a long-term field trial in Michigan, soil respiration outperformed the PSNT and leaf chlorophyll content methods for estimating early-season corn N (Culman et al., 2013). These results demonstrate the potential importance and sensitivity of soil respiration in estimating in-season N fertilizer rate recommendations and since N fertilizer is imperative to corn production, the relationship between N fertilizer and soil respiration warrants further investigation.

The objectives of this research were to 1) examine the effect of at-planting N fertilizer rate on soil respiration, and 2) determine whether measured soil respiration values relate to EONR for corn grown over a geographically diverse set of soils and weather conditions across the U.S. Midwest Corn Belt.

2.3 Materials and Methods

2.3.1 Sites and Nitrogen Treatments

This research was conducted as part of 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 DuPont Pioneer (Kitchen et al., 2017). This project is commonly referred to as the, “Performance and Refinement of Nitrogen Fertilization Tools” project. The approach for this research was fundamental N fertilizer application response field-plot studies conducted with standardized protocols and methods across a wide range of soil and weather conditions. Yield and soil measurements from these plot studies provided the measurements needed to generate N recommendations as well as N response functions.

Forty-nine corn N response trials were conducted during 2014 to 2016 in eight Midwestern Corn Belt States. In each state, two sites ranging in productivity were selected for each growing season, giving six sites per state (Missouri had three in 2016; Figure 2.1). 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 hybrids (DuPont Pioneer, Johnstown, IA) found suitable for the selected sites within the region. Most research sites followed soybean, however five sites followed corn. There were five tile drained sites and eight irrigated sites. All but 14 sites received at least some form of tillage. Planting dates ranged from April 6 – May 23. Descriptions of management for all sites are presented in Table 2.1.

Plot dimensions were state and site dependent and were determined by the planting (planter width) and harvesting (combine width) equipment available, but minimal plot harvest area was 18.6 m^2. Average size per site was 0.4 ha. Sixteen different N application treatments, replicated four times (totaling 64 plots per site), were used in a randomized complete block design (Table 2.2). Nitrogen treatments were obtained using dry-prilled NH_4NO_3 fertilizer broadcast applied. The “at-planting” fertilizer was applied within 48 hours of initial planting while the topdress fertilizer was applied between the V8 to V10 leaf stage. Treatment one was the non-fertilized control. Treatments 2 to 8 received all N at-planting in 45 kg N ha^{-1} increments from 45 to 315 kg N ha^{-1}, while treatments 9 to 14 received 45 kg N ha^{-1} at-planting and the rest at topdress in 45 kg N ha^{-1} increments from 45 to 270 kg N ha^{-1}. Treatments 15 and 16 received 90 kg N ha^{-1} at-planting with the remaining N at topdress. However, for this analysis only the 0, 45, and 225 kg N ha^{-1} at-planting N fertilizer rates were used.

2.3.2 Original Soil Sampling and Previous Analysis

Soil characterization analyses were performed for all 49 site locations. Two adjacent 1.2 m deep soil cores with a diameter of 4.76 cm were obtained from each of the four replications at each site using a Giddings Model #5-UV / MGSRPSUV (Giddings Machine Company, Windsor, CO). The location of both soil cores in each replication was determined using a soil apparent electrical conductivity (EC_a) survey map performed just prior to sampling, such that core sites represented the range of soil differences within a site as observed by soil EC_a. Both drilled cores were laid side-by-side and characterized and separated by horizon. One core was used to calculate bulk density (BD) and soil moisture while the other was processed and sent to the University of Missouri Soil Health Assessment Center for additional property analyses. Analyses included the following: particle size determination through the pipette method, cation exchange capacity (CEC), total carbon, total organic carbon, total inorganic carbon, SOM, pH (salt and water), and BD. Amount of clay (i.e. %clay) was calculated by using the particle size determination (R. Burt and Soil Survey Staff, 2014; Nelson and Sommers, 1996). Also, an anaerobic potentially mineralizable N test was performed on soil samples collected for this project but were not initially part of this analysis. These samples were incubated for seven days and then analyzed for NH_4^+-N. Initial NH_4^+-N values were subtracted from the 7-day NH_4^+-N amounts resulting in a net potentially mineralizable N (PMN). Further details are described in Clark et al (2018). The soil samples listed above were then depth weighted by 0 – 30 and 0 – 60 cm increments.

Only for the 2016 growing season were samples taken and analyzed specifically for soil respiration (Kitchen et al., 2017; Yost et al., 2018). Soil samples were taken prior to planting at three different depth increments, 0 – 5, 5 – 15, and 15 – 30 cm. The 0 – 5 and 0 – 15 samples were aggregated together by rep. Yost et al (2018) used these samples to examine the Haney test on a site-level basis. Following the analysis by Yost et al (2018), all soil samples were placed in storage for two years.

For all growing seasons (2014 – 2016), 0 – 30 cm V5 soil samples were taken and analyzed for soil nitrate and the dry samples placed in storage that was neither heated or cooled (Kitchen et al., 2018). In the spring of 2018, the V5 0, 45, and 225 kg N ha^{-1} at-planting N fertilizer treatment soil samples for each rep were retrieved from storage along with the soil samples used by Yost et al (2018). These were sub-sampled and prepared for soil respiration tests for this study.

2.3.3 Cornell Soil Respiration Test

Referred to as a sealed chamber alkali trap respirometry test, the Cornell Soil Health Assesment (CASH) soil respiration test (Moebius-Clune et al., 2016) measures soil biological activity through the output of CO_2 during a 4-day incubation period (Zibilske, 1994). While the CASH protocol was used for this analysis, the soil respiration tests were performed in the USDA-ARS Soil Quality Lab on the University of Missouri campus. In short, the protocol requires air dried soil samples to be sieved to 8 mm, however the soils for this analysis were sieved to 2 mm. The 20 g soil samples were placed in pre-perforated aluminum weigh boats (nine pin holes in the bottom). Filter paper (No. 8) was placed at the bottom of a one pint, wide mouth, “Ball” brand Mason jar, and the aluminum weigh boat containing the 20 g soil sample was placed on top of the filter paper. The trap assembly (a 4-cm tall plastic pedestal glued to the bottom of a 10 ml beaker) was placed in the aluminum weigh boat on top of the soil sample. Using a pipette, 9 ml of 0.5 M potassium hydroxide (KOH) was placed in the 10 ml beaker. Immediately following, 7.5 ml of deionized water was added to the filter paper to allow for capillary rewetting of the soil sample. The two piece Mason jar lid was then screwed on. One Mason jar with no soil (referred to as a blank) and one with reference soil were added for every 25 normal samples. The Mason jars were then placed in a jar rack to prevent disturbance over the 4-day incubation period. Further CASH protocol descriptions can be found in the Cornell Soil Health Assessment training manual (Moebius-Clune et al., 2016).

Following the completion of the incubation period an electrical conductivity (EC) probe was used to measure and record the EC of the KOH in each 10 ml beaker. The following steps were used to calculate mg CO_2-C kg^{-1} soil:

1. Prepare and determine the KOH trap "capacity" or the maximum amount of CO_2 concentration in 0.5 M KOH. This was accomplished using the equation below:

$$0.009\,L \times 0.25\,mol\,L^{-1} \times 44\,g\,mol^{-1} \times 1000\,mg\,g^{-1} = 99.025\,mg\,CO_2 \qquad [1]$$

where 0.009 L was the amount of KOH added to each sample, 0.25 mol L^{-1} was the molar relationship between KOH and CO_2 (one mole of KOH accommodated 0.5 mole of CO_2), 44 g mol^{-1} was the molecular weight of CO_2, and 1000 mg g^{-1} was the conversion from grams to milligrams.

2. Record the EC value of the KOH trap at "capacity".
3. Record the EC value of pure KOH.
4. Calculate the proportion of the trap capacity for CO_2 absorption that was actually used. This was accomplished using Eq [2]:

$$\left((EC_{raw} - EC_{sample}) \div (EC_{raw} - EC_{sat})\right) = P \qquad [2]$$

where EC_{raw} was the EC value of pure KOH, EC_{sample} was the EC of the KOH post 4-day incubation, EC_{sat} was the EC value of the KOH trap at capacity, and P is the proportion of the trap capacity that was actually used.

5. Determine the amount of CO_2 absorbed over the 4-day incubation period by using Eq [3]:

$$P \times 99.025\, mg\, CO_2 = T \qquad [3]$$

where P was the proportion of the trap capacity used, 99.025 mg CO_2 was the maximum amount of CO_2 accommodated by the trap, and T (measured in mg) was the total amount of CO_2 absorbed over the incubation period.

6. Calculate the amount of CO_2 – C kg^{-1} soil using Eq [4]:

$$(T \div 20\, g) \times 1000\, g\, kg^{-1} \times (12\, g\, mol^{-1} \div 44\, g\, mol^{-1}) = mg\, CO_2 - C\, kg^{-1}\, soil \quad [4]$$

where T was the total amount of CO_2 absorbed over the incubation period, 1000 g kg^{-1} was used to convert from g of soil to kg of soil, 12 g was the atomic weight of C, and 44 g was the molecular weight of CO_2.

A total of three comparison tests were performed on nine of the 17 sites sampled in Yost et al (2018) to justify relating 0 – 30 cm V5 soil respiration to the end-of-season calculated EONR for each of the 49 sites (Table 2.3). The nine chosen sites were selected in an attempt to cover the range of soil respiration observed by the Solvita CO_2-Burst (24 hr CO_2-Burst; Yost et al., 2018). These comparison tests are listed in Table 2.3 and include the relationships between 1) Yost et al (2018) 24 hr CO_2-Burst measurements (0 -15 cm; 24 hr_{15}) and CASH soil respiration (0 – 15 cm; $CASH_{15}$), 2) $CASH_{15}$ and pre-plant 0 – 30 cm CASH soil respiration (pp $CASH_{30}$), and 3) pp $CASH_{30}$ and V5 0 – 30 cm CASH soil respiration (V5 $CASH_{30}$). It should be noted that the V5 $CASH_{30}$ soil samples were lost for one of the nine sites chosen for the above comparison tests (2016 MN, Becker). Therefore, only eight sites were included in comparison test 3. The resulting relationship from comparison 3 was then used to estimate V5 $CASH_{30}$ for the missing site (Table 2.3).

2.3.4 Statistical Analyses

All data were analyzed using SAS 9.2 (SAS Institute Inc., Cary, NC) with a $\alpha = 0.05$. Soil respiration results were examined and compared to other soil measurements. These analyses were necessary to determine the validity of this dataset and to establish confidence in using it further. Using linear regression, soil respiration was examined as a function of, 1) % soil organic matter and % total soil organic carbon, 2) initial NH_4^+-N amount and PMN and, 3) % clay in the top 30 cm of soil.

A within-site analysis was performed to determine the effect of N fertilizer rate on soil respiration using PROC GLM MANOVA. This function allows for a multivariate analysis of variance with missing dependent variables. This was necessary since some sites had missing soil respiration values. Also, a similar analysis was performed across all 49 site locations to determine a regional difference between N fertilizer rate and soil respiration.

When relating to site-level EONR, soil respiration results were averaged across replications for site-level comparisons. Correlation analyses between soil respiration tests, sample depth, sample timings, and EONR were performed using linear regression. The EONR was calculated for all 49 site years using treatments 1, 2 and 9-14 (Table 2.2) as shown:

$$EONR = \frac{(-b-(ratio)}{(2c)} \qquad [5]$$

where *b* and *c* = linear and quadratic response coefficients from optimized quadratic function, and ratio = \$0.88 kg^{-1} N/\$0.03 kg^{-1} grain (i.e., N price/corn price). The EONR was set to not exceed the maximum N rate (315 kg N ha $^{-1}$). Additional EONR calculation details can be found in Kitchen et al. (2017).

2.4 Results and Discussion

2.4.1 Soil Respiration Related to Other Soil Properties

The V5 $CASH_{30}$ soil respiration measurements were sensitive to variations in % soil organic matter and % total organic C, with r^2 values of 0.49 and 0.67, respectively (Table 2.4; Figures 2.2 and 2.3). As % soil organic matter and % total organic C increased, V5 $CASH_{30}$ soil respiration also increased. This was expected as soil microbes use soil organic C as an energy source in the synthesis of new cells and other biological processes (Sylvia et al., 2005). A significant end product of such microbial metabolism is CO_2. Therefore, as more organic C is available, greater microbial respiration occurs. While % soil organic matter and % total organic C tests are similar in focus, the difference in correlation to V5 $CASH_{30}$ soil respiration was expected. Soil organic matter encompasses all organic residues, while total organic C is specific to the C fraction of soil organic matter.

The V5 $CASH_{30}$ soil respiration measurements were additionally related to initial NH_4^+-N and PMN amounts (Table 2.4; Figure 2.4). A significant positive linear relationship was observed. While not particularly strong, this observation is similar to those found by others (Franzluebbers et al., 1996; Franzluebbers et al., 2000; Franzluebbers and Haney, 2017). Low correlation values may be attributed to several factors. First, though soil samples are from the same site and growing season, the samples used for soil respiration (sampled at V5) analysis were unique to those used for NH_4^+-N and PMN (sampled pre-plant) analyses (Clark et al., 2018). Second, as dry soil is rewetted N is immobilized by the demands of the activated microbial population (Franzluebbers et al., 2000). Third, soils with wider C:N ratios (>20:1) immobilize N as microbes scavenge for inorganic N (Sylvia et al., 2005). Consequently, soil respiration is high while PMN is low. These relative differences could vary considerably from one site to the next. Some have observed more accurate and similar PMN results during longer incubation periods (Franzluebbers et al., 2000). When averaged across all 49 site locations, initial NH_4^+-N amounts increased by a factor of 4.3 following the 7-day incubation period. Others have found similar results (Basak and Biswas, 2014). The sites with the greatest PMN were those with the most organic matter. In general, soils with greater amounts of organic matter can sustain a larger microbial population, which ultimately has the capability of mineralizing more N (Carter and Rennie, 1982; Doran, 1987; Franzluebbers et al., 1994).

Additionally, % clay was also found to be related to V5 $CASH_{30}$ soil respiration with respiration increasing as clay content increased (Table 2.4; Figure 2.5). While conflicting results exist, others have made similar observations (Franzluebbers 1998; Cable et al., 2008). One possible explanation for the results of this study was the soil samples were sieved to 2 mm (instead of the 8 mm sieve size defined in the CASH soil respiration protocol). As soil aggregates, held together by clay particles and organic C, are broken into small pieces, additional C is made available for microbial consumption that would have otherwise been protected (Franzluebbers and Haney, 2017).

The above comparisons are similar to those of previous research and verify the sensitivity of the V5 $CASH_{30}$ soil respiration test to other soil properties. Therefore, these results were determined to be valid and could be used to address the stated primary objectives of this research.

2.4.2 Soil Respiration and N Fertilizer Rate

Across all years and sites there was no significant difference in V5 $CASH_{30}$ soil respiration measurements between the at-planting 0, 45, and 200 kg N ha^{-1} N fertilizer rates (Table 2.4). However, when analyzed by site, soil respiration between the three N fertilizer rates was found significantly different for five site locations (Figure 2.6). At four of the five sites, soil respiration decreased with N fertilization. While added N fertilizer increases the labile pool of N, changes in soil pH and other soil and plant growth factors are also likely, ultimately altering the soil microbial environment (Jones and Shannon, 1999). The pH values for these four sites were all < 6.4. As N fertilizer was added to the microbial environment (in the form of ammonium-nitrate) nitrification rates rose followed by a decrease in soil pH and therefore a decline in microbial activity and soil respiration. The decline in pH was likely greater in the microbial rich rhizosphere as ammonium-based fertilizers are known to reduce rhizosphere pH (Sylvia et al., 2005).

The remaining site had the opposite relationship, a significant increase in soil respiration as a much higher rate of inorganic fertilizer was added. The pH at this site was 7.9 and therefore microbial activity was not limited by soil pH. This site also had the highest total C (twice as much as the next highest site) and the lowest PMN suggesting the microbial community was N limited. Therefore, as more inorganic N fertilizer was added soil respiration increased. Similar results have been documented by others. Some have found inorganic N fertilizer amendments either enhanced (Pregitzer et al., 2000; Burton et al., 2002; Bowden et al., 2004) or suppressed respiration (Burton et al., 2002; Bowden et al., 2004; Foereid et al., 2004). Others have reported added N fertilizer has no effect on C mineralization (Shields et al., 1974; Kowalenko et al., 1978; Rochette and Gregorich, 1998). These mixed findings are thought to be a function of the type and amount of the N fertilizer applied, environmental conditions (including temperature and precipitation regimes), soil characteristics (how much N is already available for microbial use), and the type of vegetation grown (Meier et al., 1993; Beyer, 1994, Franzluebbers et al., 2000). As observed with this analysis, the relationship between soil respiration and added inorganic N fertilizer is unclear and has been perceived to have contradictory observations and warrants further investigation into the controlling factors governing soil respiration when N fertilizer is applied.

Due to the general lack of relationship between soil respiration and at-planting N fertilizer amount when considering all site locations, the V5 $CASH_{30}$ soil respiration amounts for each site were averaged across N rates for the remaining analyses.

2.4.3 Impact of Storage and Respiration Method Compared

Before the respiration results of this study could be used to address the objective of relating soil respiration to EONR, several additional comparisons were conducted as summarized in Table 2.3. Across the nine sites chosen for initial analysis and using the stored samples from Yost et al (2018), $CASH_{15}$ soil respiration measurements were significantly related to the 24 hr_{15} (Fig 2.7; α = 0.05; sample set 1 compared to sample set 2 in Table 2.3). Overall, soil respiration amounts were about three times greater using the CASH soil respiration test than the 24 hr CO_2-Burst, a difference that could be attributed to the incubation length (Franzluebbers and Haney, 2017). The 24 hr CO_2-Burst test has an incubation length of 24 hrs while the CASH soil respiration test calls for a 4-day incubation. Naturally, the longer incubation time allows for more CO_2 to be respired. Since the incubation method from these two times was different, nothing can be said definitively about the effect of soil sample storage difference of nearly 2 years. However, since the order of respiration increase found with CASH over the 24 hr CO_2-Burst approximates the incubation time difference, it can be presumed that sample storage for two years had a minor effect on soil respiration. Sites with low respiration measurements prior to storage were low following storage. While dependent on the desired soil analysis, this is similar to the observations made by others and suggests if soil samples are correctly processed and stored, future soil respiration tests are valid and comparable (Jones and Shannon, 1999).

Both soil respiration tests (24 hr CO_2-Burst v. CASH) use the process of rewetting dry soil, via capillary forces, to propagate suitable conditions for microbial activity and the release of CO_2. However, the means of capturing and measuring the released CO_2 is different. At the time of analysis (spring 2016; Yost et al., 2018), the 24 hr lab test protocol used Solvita specific detector probes. Prior to the start of the 24 hr incubation a CO_2 colorimetric detector probe was inserted into the test jar. Following incubation, the probe was removed and inserted into a Solvita Digital Color Reader. The digital colorimetric value was then converted to mg kg^{-1} CO_2-C. This specific method is relatively expensive for quantifying soil respiration, and dependent on the specific detector probe used. However, detector probes can become saturated for soils with high soil respiration, resulting in an underestimation of findings (Woods End Laboratories, 2016; McGowen et al., 2018). Cost for the CASH soil respiration test using the potassium hydroxide beaker trap is less since it does not rely on detector probes or a Digital Color Reader. While the incubation length is longer and less convenient in that sense, the findings of this research suggest the CASH soil respiration test is just as informative and may be more easily adopted by some producers.

2.4.4 Sample Depth and Timing

The $CASH_{30}$ soil respiration measurements taken from stored Yost et al (2018) samples were highly related to the $CASH_{15}$ measurements (sample set 1 compared to sample set 3 in Table 2.3; Figure 2.8; standard error = 0.04 mg CO_2-C kg^{-1} soil). In general, the $CASH_{15}$ soil respiration measurements were ~50% higher than those from the $CASH_{30}$. With increasing soil sample depth, soil organic matter and soil microbial activity decrease (Fang and Moncrieff, 2005; Franzluebbers, 2018). Thus, it is not surprising the shallower depth yielded more soil respiration than the deeper depth. These results show that soil collected for standard 15 – 20 cm soil fertility tests may be used for soil respiration analyses ultimately increasing the likelihood of producer adoption. Likewise, deeper soil respiration measurements could confidently be used to estimate soil surface respiration rates and vice versa.

The V5 $CASH_{30}$ soil respiration measurements were related to the pre-plant $CASH_{30}$ soil respiration measurements recorded from the Yost et al (2018) sub-samples (sample set 3 compared to sample set 4 in Table 2.3; Figure 2.9). These results are similar to those observed by others. A correlation between soil respiration and grain yield, total biomass, and total N was found to be similar at the pre-plant, V5, and V10 soil sampling times (Culman et al., 2013). On average, V5 $CASH_{30}$ soil respiration was ~40 mg CO_2-C kg^{-1} soil greater than the pp $CASH_{30}$ samples. This was likely due to plant growth (Culman et al., 2013). Plant roots excrete nutrient and C rich exudates into the rhizosphere allowing for the consortia of soil microorganisms to flourish (Sylvia et al., 2005). Generally, soil respiration mirrors a bell-shaped curve through the growing season. Namely, soil respiration is less in the spring followed by an increase during the mid-season, and finally a decrease during the late summer and early fall as soils generally are drier and corn plants senesce (Willson et al., 2001; Culman et al., 2013).

2.4.5 Relating EONR to C Respiration

Considering all years and sites (n=49) EONR was weakly correlated to the V5 $CASH_{30}$ soil respiration measurements (sample set 5 in Table 2.3; Figure 2.10). Generally, as soil respiration increased the amount of N fertilizer needed to reach EONR decreased. Soils with greater amounts of microbial activity (i.e. soil respiration) likely mineralized more N ultimately lowering the total inorganic N fertilizer needed to reach EONR. An analysis by year revealed soil respiration was most strongly correlated to EONR in the 2016 growing season (Figure 2.11), the only year previously reported from this regional study (Yost et al., 2018). The 2016 growing season may have mirrored the microbial activity observed in this laboratory analysis. The 2014 and 2015 soil respiration results as a representation of soil microbial activity was much less related to corn N need. Undoubtedly weather-driving factors of soil microbial activity throughout the growing season of each year are unique, and so lab-measured soil respiration may or may not be an accurate estimation of the actual field soil respiration, factors primarily related to varying soil temperature and moisture.

2.5 Conclusion

The 24 hr CO_2-Burst and CASH soil respiration tests were significantly related to one another signifying test type and soil sample storage had little effect on the patterns of soil respiration (i.e. soils with low respiration before storage will have low respiration following storage). Consequently, the less expensive CASH soil respiration test may be easier to implement or adopt. And, if processed correctly, stored soil samples could be used for future respiration analysis. Soil respiration values from different depths and timings were highly correlated, supporting sampling to 15 cm before or after planting was sufficiently the same for respiration analysis. Adding inorganic N fertilizer at planting had no significant effect on soil respiration measurements when examined across all sites, though the effect was seen for a few sites. Due to the varying results found by others and those from this analysis, further research is needed to determine the role of increasing amounts of inorganic N fertilizer on soil respiration.

The negative relationship observed between EONR and V5 soil respiration supports soils with greater respiration provide more plant available N, ultimately lowering the need for additional inorganic N fertilizer. However, this relationship was more evident in one year than the other two, and illustrates how this comparison is quite dependent on temporal variability. Therefore, caution should be given when using soil respiration to estimate in-season N fertilizer recommendations.

2.6 Bibliography

Aber, J.D., A. Magill, R. Boone, J.M. Melillo, P. Steudler, and R. D. Bowden. 1993. Plant and soil responses to three years of chronic nitrogen additions at the Harvard Forest, Petersham, MA. Ecol. Appl. 3:156-166.

Alvarez, R., and C.R. Alvarez. 2000. Soil organic matter pools and their associations with carbon mineralization kinetics. Soil Sci. Soc. Am. J. 64:184-189

Barker, D.W., J.E. Sawyer, M.M. Al-Kaisi, and J.P. Lundwall. 2006. Assessment of the amino sugar-nitrogen test on Iowa soils: II. Field correlation and calibration. Agron. J. 98:1352-1358. doi: 10.2134/agronj2006.0034

Basak, B.B., and D.R. Biswas. 2014. Carbon and nitrogen mineralization in soil amended with value-added manures and fertilizers under varying temperature and soil moisture regimes. J. of the Indian Soc. of Soil. Sci. 62:18-28.

Beyer, L. 1994. Effect of cultivation on physicochemical, hums chemical and biotic properties and fertility of two forest soils. Agric. Ecosyst. Environ. 48:179-188.

Biggs, G.L., T.M. Blackmer, T.H. Demetriades-Shah, K.H. Holland, J.S. Schepers, and J.H. Wurm. 2002. Method and apparatus for real-time determination and application of nitrogen fertilizer using rapid, non-destructive crop canopy measurements. U.S. Patent 6,393,927. Date issued: 28 May.

Bowden, R.D., E. Davidson, K. Savage, C. Arabia, and P. Steudler. 2004. Chronic nitrogen additions reduce total soil respiration and microbial respiration in temperate forest ssoils at the Harvard forest. For. Ecol. Manage. 196:43-56.

Brookes, P.C., A. Landman, G. Pruden, D.S. Jenkinson. 1985. Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Bio. Biochem. J. https://doi.org/10.1016/0038-0717(85)90144-0

Burton, A.J., K.S. Pregitzer, R.W. Reuss, R.L. Hendrick, and M.F. Allen. 2002. Root respiration in North American forests: effects on nitrogen concentration and temperature across biomes. Oecologia 131:559-568.

Cable, J.M., K. Ogle, D.G. Williams, J. F. Weltzin, T. E. Huxman. 2008. Soil texture drives responses of soil respiration to precipitation pulses in the sonoran desert: Implications for climate change. Ecosystems 11:961.https://doi.org/10.1007/s10021-008-9172-x

Cabrera, M.L., and D.E. Kissel. 1998. Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. Soil Sci. Soc. Am. J. 52:1027-1031.

Cao, M., and F.I. Woodward. 1998. Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. Nature 393:249-252.

Carter, M.R., and R.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: Distribution of microbial biomass and mineralizable C and N potentials. Can. J. Soil Sci. 62:587-597

Clark, J. 2018. Improving nitrogen management with the anaerobic potentially mineralizable nitrogen test. PhD dissertation. Retrieved from the University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/199092

Culman, S.W., S.S. Snapp, M.A. Freeman, M.E. Schipanski, J. Beniston, R. Lal, L.E. Drinkwater, A.J. Franzluebbers, J.D. Glover, A.S. Grandy, J. Lee, J. Six, J.E. Maul, S.B. Mirksy, J.T. Spargo, M.M. Wander. 2012. Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. Soil Sci. Soc. Am. J. 76:494-504. doi: 10.2136/sssaj2011.0286.

Culman, S.W., S.S. Snapp, J.M. Green, and L.E. Gentry. 2013. Short- and long-term labile soil carbon and nitrogen dynamics reflect management and predict corn agronomic performance. Agron. J. 105:493-502. doi:10.2134/agronj2012.0382

Delphin, J.E. 2000. Estimation of nitrogen mineralization in the field from an incubation test and from soil analysis. Agronomie 20:349-361

Doran, J.W. 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fertil. Soils 5:68-75

Doran, J., T. Kettler, and M. Tsivou. 1997. Field and laboratory Solvita soil test evaluation. Manuscript Univ. Nebraska USDA-Agricultural Research Service. Lincoln.

Fang, C., and J.B. Moncrieff. 2005. The variation of soil microbial respiration with depth in relation to soil carbon composition. Plant and Soil 268:243-253. doi:https://doi.org/10.1007/s11104-004-0278-4

Foereid, B., A, de Neergaard, and H. Hogh-Jensen. 2004. Turnover of organic matter in a Miscanthus field: Effect of time in Miscanthus cultivation and inorganic nitrogen supply. Soil Biol. Biochem. 36:1075-1085.

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer. 1994a. Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Sci. Soc. Am. J. 58:1639-1645

Franzluebbers, A.J., R.L. Haney, F.M. Hons, and D.A. Zuberer. 1996. Determination of microbial biomass and nitrogen mineralization following rewetting of dried soil. Soil Sci. Soc. Am. J. 60:1133-1139. doi: 10.2136/sssaj1996.03615995006000040025x

Franzluebbers, A.J., R.L. Haney, C.W. Honeycutt, H.H. Schomberg, and F.M. Hons. 2000. Flush of carbon dioxide following rewetting of dried soil relates to active organic pools. Soil Sci. Soc. Am. J. 64:613-623. doi: 10.2136/sssj2000.642613x

Franzluebbers, A.J., F.M. Hons, D.A. Zuberer. 1998. In situ and potential CO_2 evolution from a Fluventic Ustochrept in southcentral Texas as affected by tillage and cropping intensity. Soil and Tillage Research 47, 303-308.

Franzluebbers, A.J. 1999. Potential C and N mineralization and microbial biomass from intact and increasingly disturbed soil of varying texture. Soil Bio. and Biochem. 31:1083-1090

Franzluebbers, A.J., Haney, R.L. 2017. Evaluation of soil processing conditions on mineralilzable C and N across a textural gradient. Soil Sci. Am. J. doi:10.2136/sssaj2017.08.0275

Franzluebbers, A.J. 2018. Soil-test biological activity with the flush of CO_2: III. Corn yield responses to applied nitrogen. Soil. Sci. Soc. Am. J 82:708-721. doi: 10.2136/sssaj2018.01.0029

Gagnon, B., R. Lalande, and S.H. Fahmy. 2001. Organic matter and aggregation in a degraded potato soil as affected by raw and composted pulp residue. Biol. Fertil. Soils 34:441-447

Ghani, A., M. Dexter, and K. Perrott. 2003. Hot-water extractable carbon in soils: A sensitive measurement of determining impacts of fertilization, grazing, and cultivation. Soil Biol. Biochem. 35:1231-1243. doi: 10.1016/S0038-0717(03)00186-X

Gregorich, E.G., M.H. Beare, U. Stoklas, and P. St-Georges. 2003. Biodegradability of soluble organic matter in maize-cropped soils. Geoderma 113:237-252.

Griffin, T.S., 2008. Nitrogen in agricultural systems, Agronomy Monograph 49. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, 677 S. Segoe Rd., Madison, WI 53711, USA.

Groot, J.R., and V.J.G. Houba. 1995. A comparison of different indices for nitrogen mineralization. Biol. and Fert. of Soils. 19, pp. 1-9.

Hadas, A., S. Feigenbaum, A. Feigin, and R. Portnoy. 1986. Nitrogen mineraliztion in profiles of differently managed soil types. Soil Sci. Soc. Am. J. 50:314-319.

Haney, R.L., and E.B. Haney. 2010. Simple and rapid laboratory method for rewetting dry soil for incubations. Commun. Soil Sci. Plant Anal. 41(12): 1493–1501.

Haney, R.L., F.M. Hons, M.A. Sanderson, and A.J. Franzluebbers. 2001. A rapid procedure for estimating nitrogen mineralization in manured soil. Biol. Fertil. Soils 33(2): 100–104.

Haney, R.L., A.J. Franzluebbers, V.L. Jin, M.-V. Johnson, E.B. Haney, M.J. White, and R.D. Harmel. 2012. Soil organic C:N vs. water-extractable organic C:N. Open J. Soil Sci. 2(3): 269–274.

Haney, R.L., E.B. Haney, D.R. Smith, and M.J. White. 2015. Estimating potential nitrogen mineralisation using the Solvita soil respiration system. Open J. Soil Sci. 5(5): 319–323.

Harmel, R.D., and R.L. Haney. 2013. Initial field evaluation of the agro-economic effects of determining nitrogen fertilizer rates with a recently-developed soil test methodology. Open J. Soil Sci. 3(2): 91–99.

Hassink, J., A.M. Neutel, and P.C. De Ruiter. 1994. C and N mineralization in sandy and loamy grassland soils: The role of microbes and microfauna. Soil. Biol. Biochem. 26:1565-1571

Hurisso, T.T., S.W. Culman, W.R. Horwath, J. Wade, D. Cass, J.W. Beniston, T.M. Bowles, A.S. Grandy, A.J. Franzluebbers, M.E. Schipanski, S.T. Lucas, C.M. Ugarte. 2016. Comparison of permanganate-oxidizable carbon and minearlizable carbon for assessment of organic matter stabilization and mineralization. Soil Sci. Soc. Am. J. 80:1352-1364. doi: 10.2136/sssaj2016.04.0106.

Idowu, O.J., H.M. Es, G.S. Abawi, D.W. Wolfe, J.I. Ball, B.K. Gugino et al. 2008. Farmer-oriented assessment of soil quality using field laboratory, and VNIR spectroscopy methods. Plant Soil 307:243-253. doi: 10.1007/s11104-007-9521-0

Jokela, W.E., and G.W. Randall. 1989. Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. Agron. J. 81:720-726. doi:10.2134/agronj1989.00021962008100050004x

Jones, D.L. and D. Shannon. 1999. Mineralization of amino acids applied to soils impact of soil sieving, storage, and inorganic nitrogen additions. Soil Sci. Soc. Am. J. 63:1199-1206. doi: 10.2136/sssaj1999.6351199x

Kitchen, N.R., K.A. Sudduth, S.T. Drummond, P.C. Scharf, H.L. Palm, D.F. Roberts, and E.D. Vories. 2010. Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. Agron. J. 102:71-84. doi:10.2134/agronj2009.0114

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

Kowalenko, C.G., K.C. Ivarson, and D.R. Cameron. 1978. Effect of moisture content, temperature and nitrogen fertilization on carbon dioxide evolution from field soils. Soil Biol. Bio-chem. 19:417-423.

Laboski, C.A.M., J.E. Sawyer, D.T. Walters, L.G. Bundy, R.G. Hoeft, G.W. Randall, and T.W. Andraski. 2008. Evaluation of the Illinois soil nitrogen test in the north central region of the United States. Agron. J. 100:1070-1076. doi:10.2134/agronj2007.2085

Lee, B.Y., N. Lorenz, L.K. Dick, and R.P Dick. 2007. Cold storage and pretreatment incubation effects on soil microbial properties. Soil Sci. Soc. J. 71:1299-1305. doi:10.2136/sssaj2006.0245

Lehmann, J., M. Kleber. 2015. The contentious nature of soil organic matter. Nature 528, 60-68.

Liljeroth, E., J.A. Van Veen, and H.J. Miller. 1990. Assimilate translocation to the rhizosphere of two wheat lines and subsequent utilization by rhizosphere microorganisms at two soil nitrogen concentrations. Soil Biol. Biochem. 22:1015-1021.

Mclauchlan, K.K., S.E. Hobbie. 2004. Comparison of labile soil organic matter fractionation techniques. Soil Sci. Soc. Am. J. 68:1616-1625

McGowen, E.B., S. Sharma, S.D. Deng, H. Zhang, and J.G. Warren. 2018. An automated laboratory method for measuring CO_2 emissions from soils. Agric. Environ. Lett. 3:180008. doi:10.2134/ael2018.02.0008.

Meier, J.N., J.W. Fyles, A.F. Mackenzie, and I.P. Ohalloran. 1993. Effects of lignosulfonate-fertilizer applications on soil respiration and nitrogen dynamics. Can. J. Soil Sci. 73:233-242.

Moebius-Clune, B.N., D.J. Moebius-Clune, B.K. Gugino, O.J. Idowu, R.R. Schindelbeck, A.J. Ristow,…G.S. Abawi. 2016. Comprehensive Assessment of Soil Health: The Cornell Framework Manual (3.1 ed.).

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

Mulvaney, R.>, S.A. Khan, and T.R. Ellsworth. 2006. Need for a soil-based approach in managing nitrogen fertilizers for profitable corn production. Soil Sci. Soc. Am. J. 70:172-182. doi:10.2136/sssaj2005.0034

Osterhaus, J.T., L.G. Bundy, and T.W. Andraski. 2008. Evaluation of the Illinois soil nitrogen test for predicting corn nitrogen needs. Soil Sci. Soc. Am. J. 72:143-150. doi:10.2136/sssaj2006.0208

Pastor, J., B. Dewey, R.J. Naiman, P.F. McInnes, and Y. Cohen. 1993. Moose browsing and soil fertility in the boreal forests of Isle Royale National Park. Ecology 74:467-480

Pregitzer, K.S., D.R. Zak, J. Maziasz, J. DeForest, P.S. Curtis and J. Lussenhop. 2000. Interactive effects of atmospheric CO_2 and soil-N availability on fine roots of Populus tremuloides. Ecol. Appl. 10:18-33.

Rasmussen, P.E., C.L. Douglas, Jr., H.P. Collins, and S.L. Albrecht. 1998. Long-term cropping system effects on mineralizable nitrogen in soil. Soil Biol. Biochem. 30:1829-1837.

Rochette, P and G.L. Hutchinson. 2005. Measurement of soil respiration in situ: chamber techniques. UNLincoln. Amer. Soc. Agron. Micrometeorology in Agricultural Systems, Agronomy monograph no. 47.

Rochette, P., and E.G. Gregorich. 1998. Dynamics of soil microbial biomass C, Soluble organic C and CO_2 evolution after three years of manure application. Can. J. Soil Sci. 78:283-290.

Russell, J.S. 1963. Nitrogen content of wheat grain as an indication of potential yield response to nitrogen fertilizer. Aust. J. Exp. Agric. Anim. Husb. 3:319-325. doi: 10.1071/EA9630319

Scharf, P.C., N.R. Kitchen, K.A. Sudduth, J.G. Davis, V.C. Hubbard, and J.A. Lory. 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. Agon. J. 97:452-461. doi: 10.2134/agronj2005.0452

Scharf P. C., D. K. Shannon, H. L. Palm, K. A. Sudduth, S. T. Drummond, N. R. Kitchen, L. J. Mueller, V. C. Hubbard, L. F. Oliveira. 2011. Sensor-based nitrogen application out-performed producer-chosen rates for corn in on-farm demonstrations. Agron. J. 103: 1683-1691. doi:10.2134/agronj2011.0164

Shanahan, J.F., K. Holland, J.S. Shepers, D.D. Francis, M.R. Schlemmer, and R. Caldwell. 2003. Use of crop reflectance sensors to assess corn leaf chlorophyll content. p. 135-150. In T. VanToai et al. (ed.) Digital imaging and spectral techniques: Applications to precision agriculture and crop physiology. ASA Spec. Publ. 66. ASA, CSSA, and SSSA, Madison, WI.

Shields, J.A., E.A. Paul, and W.E. Lowe. 1974 Factors influencing the stability of labeled microbial materials in soils. Soil Biol. Bio-chem. 6:31-37.

Singh, G., J.E. Schoonover, K.W.J. Williard, G. Kaur, J. Crim. 2018. Carbon and nitrogen pools in deep soil horizons at different landscape positions. Soil Sci. Soc. Am. J. 82:1512-1525. doi: 10.2136/sssaj2018.03.0092

Shapiro, C.A., and C.S. Wortman. 2006. Corn response to nitrogen rate, row spacing, and plant density in eastern Nebraska. Agron J. 98:529-535. doi: 10.2134/agronj2005.0137

Soil Science Society of America. 1997. Glossary of Soil science terms. Soil Science Society of America, Madison, Wis.

Stanford, G., and S.J. Smith. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. Proc. 36:465-472. Doi: 10.2136/sssaj1972.03615995003600030029x

Stanford, G., and S.J. Smith. 1978. Oxidative release of potentially mineralizable soil nitrogen by acid permanganate extraction. Soil Sci. 126:210-218.

Stecker, J.A., D.D. Buchholz, R.G. Hanson, N.C. Wollenhaupt, and K.A. McVay. 1995. Tillage and rotation effects on corn yield response to fertilizer nitrogen on Aqualf soils. Agron. J. 87:409-415. doi: 10.2134/agronj1995.00021962008700030004x

Sylvia, D.M., J.J. Fuhrmann, P.G. Hartel, D.A. Zuberer. 2005. Principles and applications of soil microbiology. Pearson Education Inc. 2nd Edition

Triplett, G.G., F. Haghiri, and D.M. van Doren. 1979. Plowing effect on corn yield response to N following alfalfa. Agron. J. 71:801-803. doi:10.2134/agronj1979.00021962007100050023x

Vanotti, M.B., and L.G. Bundy. 1994. Corn nitrogen recommendations based on yield response data. J. Prod. Agric. 7:249-256. doi:10.2134/jpal1994.0249

Wall, D.P., R. Weisz, C.R. Crozier, R.W. Heininger, and J.G. White. 2010. Variability of the Illinois soil nitrogen test across time and sampling depth. Soil Sci. Soc. Am. J. 74:2089-2100. doi: 10.2136/sssaj2009.0253

Wang, W., C.J. Smith, P.M. Chalk, and D. Chen. 2001. Evaluating chemical and physical indices of nitrogen mineralization capacity with an unequivocal reference. Soil Sci. Soc. Am. J. 65:368-376. doi: 10.2136/sssaj2001.652368x

Weil, R.R., K.R. Islam, M.A. Stine, J.B. Gruver, and S.E. Samson-Liebig. 2003. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. American Journal of Alternative Agriculture, 18(1), 3-17.

Weil, R.R., and N.C. Brady. 2015. The nature and property of soils. 15th edition. Pearson Education Limited. Essex, England

Williams, J.D., C.R. Cozier, J.G. White, R.W. Heiniger, R.R. Sripada, and D.A. Crouse. 2007. Illinois soil nitrogen test predicts southeastern US corn economic optimum nitrogen rates. Soil Sci. Soc. Am J. 71:735-744. doi:10.2136/sssaj2006.0135

Woods End Laboratories. 2016. Soil CO_2 – burst official Solvita instructions. Version 2016/1 updated for DCR Model 700.6. Woods End, Laboratories, Mt Vernon, ME.

Yost, M., K. Veum, N.R. Kitchen, J. Camberato, P. Carter, R. Ferguson, F. Fernandez, D. Franzen, C. Laboski, E. Nafziger, and J. Sawyer. 2018. Evaluation of the Haney Soil Health Nutrient Tool for corn nitrogen recommendations across eight Midwest states. J. Soil and Water Conserv. Soc.

2.7 Tables and Figures

Table 2.1. Management description for the 49 sites for the 2014 – 2016 growing seasons. Each of the eight participating states chose two contrasting locations with varying productivity.

Year	State	Site	Productivity†	Previous Crop	Tiled	Irrigated	Tillage*	Hybrid	Seed Rate	Row Space	Plant Date
									seeds/ha	cm	
2014	IA	Ames	L	SB	No	No	FC	P0987AMX	86,450	76	7 May
2014	IA	Mas	H	SB	No	No	FC	P1498AM	85,215	76	9 May
2014	IL	Brown	L	SB	No	No	SP FC/ F deep ripped	P1498AM	86,450	76	24 Apr
2014	IL	Urbana	H	SB	No	No	FC / F deep ripped	P0987AMX	86,450	76	25 Apr
2014	IN	Loam	H	SB	No	No	FC	P0987AMX	80,275	76	19 May
2014	IN	Sand	L	SB	No	No	No-till	P0987AMX	80,275	76	19 May
2014	MN	New	H	SB	No	No	F FC/ SP FC	P0157AMX	87,685	76	21 May
2014	MN	Charles	L	SB	No	No	Vertical-till	P0157AMX	85,215	76	16 May
2014	MO	Bay	L	SB	No	No	FC	P1498AM	86,450	76	2 May
2014	MO	Troth	H	SB	No	No	FC	P1498AM	86,450	76	2 May
2014	ND	Amenia	H	Corn	Yes	No	No-till	P9188AMX	83,980	56	23 May
2014	ND	Durbin	L	Corn	No	No	No-till	P9188AMX	83,980	56	23 May
2014	NE	Brandes	L	SB	No	Yes	F chisel/ SP FC	P1151HR	86,450	76	19 Apr
2014	NE	SCAL	H	SB	No	Yes	F chisel/ SP FC	P1151HR	83,980	76	7 May

2014	WI	Waz	L	SB	No	No	No-till	P0987AMX	90,155	76	7 May
2014	WI	Steuben	H	SB	No	No	No-till	P0987AMX	93,119	76	6 May
2015	IA	Boone	L	SB	No	No	FC	P0987AMX	86,450	76	18 May
2015	IA	Lewis	H	SB	No	No	FC	P1498AM	85,215	76	29 Apr
2015	IL	Brown2	L	SB	No	No	SP FC/ F deep ripped	P1498AM	86,450	76	28 Apr
2015	IL	Urbana2	H	SB	No	No	FC / F deep ripped	P0987AMX	86,450	76	23 Apr
2015	IN	Loam2	H	SB	No	No	FC	P0987AMX	80,275	76	29 Apr
2015	IN	Sand2	L	SB	No	No	No-till	P0987AMX	80,275	76	29 Apr
2015	MN	New2	H	SB	No	No	F FC/ SP FC	P0157AMX	87,685	76	18 Apr
2015	MN	Charles2	L	SB	No	No	Vertical-till	P0157AMX	85,215	76	1 May
2015	MO	Lonetree	L	SB	No	No	FC	P1498AM	86,450	76	17 Apr
2015	MO	Troth2	H	SB	No	No	FC	P1498AM	86,450	76	14 Apr
2015	ND	Amenia2	H	Corn	Yes	No	No-till	P9188AMX	83,980	56	24 Apr
2015	ND	Durbin2	L	Corn	No	No	No-till	P9188AMX	83,980	56	24 Apr
2015	NE	Brandes2	L	SB	No	Yes	F chisel/ SP FC	P1151HR	86,450	76	19 Apr
2015	NE	SCAL2	H	SB	No	Yes	F chisel/ SP FC	P1151HR	83,980	76	24 Apr
2015	WI	Belmont	L	SB	No	No	No-till	P0987AMX	90,155	76	4 May
2015	WI	Darling	H	SB	No	No	No-till	P0987AMX	93,119	76	4 May
2016	IA	Crawford	H	SB	Yes	No	Chisel	P1197AMXT	86450	76	26 Apr
2016	IA	Story	L	SB	Yes	No	Chisel	P1197AMXT	86450	76	12 May

2016	IL	Shumway	L	SB	No	No	FC/ Vertical-till	P1197AM	79040	76	25 Apr
2016	IL	Urbana	H	SB	No	No	FC	P1197AMXT	88920	76	19 Apr
2016	IN	Loam	H	SB	No	No	F Rip/ SP FC	P1197AMXT	80275	76	20 May
2016	IN	Sand	L	SB	No	No	F Chisel / SP FC	P1197AMXT	80275	76	20 May
2016	MN	Becker	L	SB	No	Yes	SP Chisel/ Rip	P0157AMX	87685	76	27 Apr
2016	MN	Waseca	H	SB	No	No	F Chisel/ FC	P0157AMX	87685	76	6 May
2016	MO	Bradford	L	SB	No	No	SP Disk/ FC	P1197AM	86450	76	16 Apr
2016	MO	Loess	H	SB	No	No	SP FC	P1197AM	83980	76	6 Apr
2016	MO	Troth3	H	SB	No	Yes	SP Disk/ FC	P1197AM	86450	76	13 Apr
2016	ND	Amenia3	H	SB	No	No	F Chisel/ FC	P9188AMX	93860	56	6 May
2016	ND	Durbin3	L	SB	Yes	No	F Chisel/ FC	P9188AMX	88920	56	6 May
2016	NE	Kyes	L	SB	No	Yes	No-till	P1197AMT	79040	76	5 May
2016	NE	SCAL3	H	Corn	No	Yes	No-till	P1197AMT	83980	76	12 May
2016	WI	Lorenzo	L	SB	No	No	No-till	P0157AMX	86450	76	23 Apr
2016	WI	Plano	H	SB	No	No	No-till	P0157AMX	86450	76	23 Apr

†L, Low; H, High; *FC, field cultivated; F, fall; Chis, Chisel; SP, spring.

Table 2.2. Sixteen different N fertilizer rates split over two times were replicated four times at each site. Treatments 1, 2, and 9-14 were used to calculate the economical N fertilizer rate for each site location. Treatments 1, 2, and 6 were used for soil respiration analysis.

Trt #	Planting N	Topdress N	Total N
	——————kg ha^{-1}——————		
1	0	0	0
2	45	0	45
3	90	0	90
4	135	0	135
5	180	0	180
6	225	0	225
7	270	0	270
8	315	0	315
9	45	45	90
10	45	90	135
11	45	135	180
12	45	180	225
13	45	225	270
14	45	270	315
15	90	90	180
16	90	180	270

Table 2.3. A series of comparison tests to relate soil respiration between methods, sample storage, depth, and sampling time.

Sample Set #	Sample Year(s)	Sample Sites	Sample Time[†]	Sample Depth	Sample Storage	C Resp. Method[††]	Comparison Test
				--cm--	months		
1	2016	17	Preplant	0 - 15	< 2	24 hr	None- results reported in Yost et al., 2018
2	2016	9	Preplant	0 – 15	~ 24	CASH	Compared to sample set #1
3	2016	9	Preplant	0 – 30	~ 24	CASH	Compared to sample set #2
4	2016	9	V5	0 - 30	~ 24	CASH	Compared to sample set #3
5	2014-16	49	V5	0 - 30	24 - 36	CASH	Compared to EONR value for each respective site

† Preplant, soil samples taken before corn was planted; V5, soil samples taken at the V5 corn growth development stage.

†† Solvita, 24 hr CO_2-Burst; CASH, Cornell Soil Health Assessment soil respiration test.

Table 2.4. Soil respiration generated by the Comprehensive Assessment of Soil Health (CASH) method at the V5 corn growth development stage for three different at-planting N fertilizer rates (0, 45, and 200 kg N ha^{-1}) at all 49 site locations. Following an ANOVA test, there was no significant difference between N fertilizer rates on a regional level. To validate the soil respiration measurements in this analysis, soil respiration amounts were compared to several other soil properties. These properties include soil organic matter, total organic C, initial NH_4^+-N, and potentially mineralizable N (PMN), and clay in the top 30 cm of soil.

Year	State	Site	EONR	0 N Resp.	45 N Resp.	200 N Resp.	Organic Matter	Tot. Org. C	Initial NH_4^+	PMN	Clay (30 cm)
			kg N ha^{-1}	mg CO_2-C kg^{-1} soil			-----------%--------		mg N kg^{-1} soil		%
2014	IA	Ames	98	.	178	185	2.6	0.80	11.1	10.8	22.5
2014	IA	Mas	97	229	220	193	3.3	0.87	15.9	20.4	28.7
2014	IL	Brown	172	158	140	109	1.6	0.38	6.1	12.1	17.0
2014	IL	Urbana	195	228	213	182	2.9	0.86	10.1	32.5	27.3
2014	IN	Loam	113	130	118	118	2.1	0.50	3.5	13.6	13.2
2014	IN	Sand	131	105	95	86	1.4	0.27	2.7	8.7	7.4
2014	MN	New	101	277	238	238	5.2	1.27	12.9	54.0	32.8
2014	MN	Charles	64	.	122	151	2.3	0.62	10.7	24.6	22.3
2014	MO	Bay	118	200	196	195	2.2	0.58	6.5	18.4	28.0
2014	MO	Troth	127	168	185	173	1.4	0.55	7.5	28.1	17.2
2014	ND	Amenia	106	.	249	228	2.9	0.87	12.5	25.6	23.8
2014	ND	Durbin	107	.	238	255	3.4	1.46	10.8	41.7	57.0
2014	NE	Brandes	181	116	134	136	1.2	0.35	5.5	14.2	6.7
2014	NE	SCAL	83	187	210	173	2.6	0.79	10.0	26.4	34.0
2014	WI	Steuben	28	296	286	243	3.0	1.46	8.1	38.0	20.1
2014	WI	Waz	66	225	196	213	2.4	0.54	8.8	19.7	24.5
2015	IA	Boone	127	167	126	143	2.9	0.87	7.2	12.9	24.1
2015	IA	Lewis	55	182	146	140	2.8	0.84	7.9	16.0	32.6
2015	IL	Brown2	71	154	117	115	1.7	0.44	5.8	23.5	16.6
2015	IL	Urbana2	172	205	185	166	2.9	0.85	8.3	30.4	25.9
2015	IN	Loam2	103	156	149	137	2.5	0.81	4.6	29.7	18.2
2015	IN	Sand2	144	119	129	84	1.4	0.40	3.1	18.6	8.9
2015	MN	New2	94	227	210	203	4.2	1.26	8.7	20.0	35.0
2015	MN	Charles2	108	165	165	179	2.3	0.84	4.2	34.1	20.9
2015	MO	Lonetree	240	162	156	158	2.4	0.60	10.8	26.4	31.4
2015	MO	Troth2	240	178	167	183	2.0	0.71	9.3	33.1	30.2
2015	ND	Amenia2	99	137	125	168	1.9	0.59	9.9	15.4	15.5
2015	ND	Durbin2	84	239	224	227	4.1	1.36	9.6	48.1	44.8
2015	NE	Brandes2	185	115	106	103	0.8	0.29	2.5	43.5	2.7
2015	NE	SCAL2	0	244	229	214	2.8	0.86	5.8	29.1	28.4
2015	WI	Belmont	0	209	178	179	2.9	0.71	3.7	31.9	19.5

2015	WI	Darling	115	267	251	244	3.7	1.09	5.1	37.9	30.1
2016	IA	Crawford	129	200	203	198	3.3	1.00	6.4	28.0	29.5
2016	IA	Story	128	209	187	191	3.1	0.94	8.1	35.7	24.6
2016	IL	Shumway	106	173	158	146	1.8	0.48	6.2	35.6	15.7
2016	IL	Urbana	118	179	177	174	3.1	0.96	8.0	28.3	25.1
2016	IN	Loam	95	167	173	168	4.2	0.87	9.5	34.2	23.9
2016	IN	Sand	66	122	.	.	1.6	0.37	7.1	25.7	8.0
2016	MN	Becker	239	92	.	.	1.9	0.45	8.0	7.9	6.0
2016	MN	Waseca	109	172	187	172	4.2	1.18	8.2	33.1	32.6
2016	MO	Bradford	131	115	119	110	2.0	0.47	6.5	26.0	24.9
2016	MO	Loess	143	149	152	139	2.4	0.68	12.9	46.0	24.4
2016	MO	Troth3	145	185	180	196	2.3	0.78	8.1	37.7	38.9
2016	ND	Amenia3	0	196	217	195	3.0	0.87	9.7	40.5	23.2
2016	ND	Durbin3	0	.	246	236	3.0	1.14	9.8	33.5	58.9
2016	NE	Kyes	120	208	190	189	2.3	0.61	5.7	32.1	17.2
2016	NE	SCAL3	13	162	147	144	2.9	0.85	6.1	35.7	28.2
2016	WI	Lorenzo	30	241	286	336	4.4	1.86	6.6	45.4	28.5
2016	WI	Plano	88	172	161	159	3.5	0.97	7.3	41.3	24.0

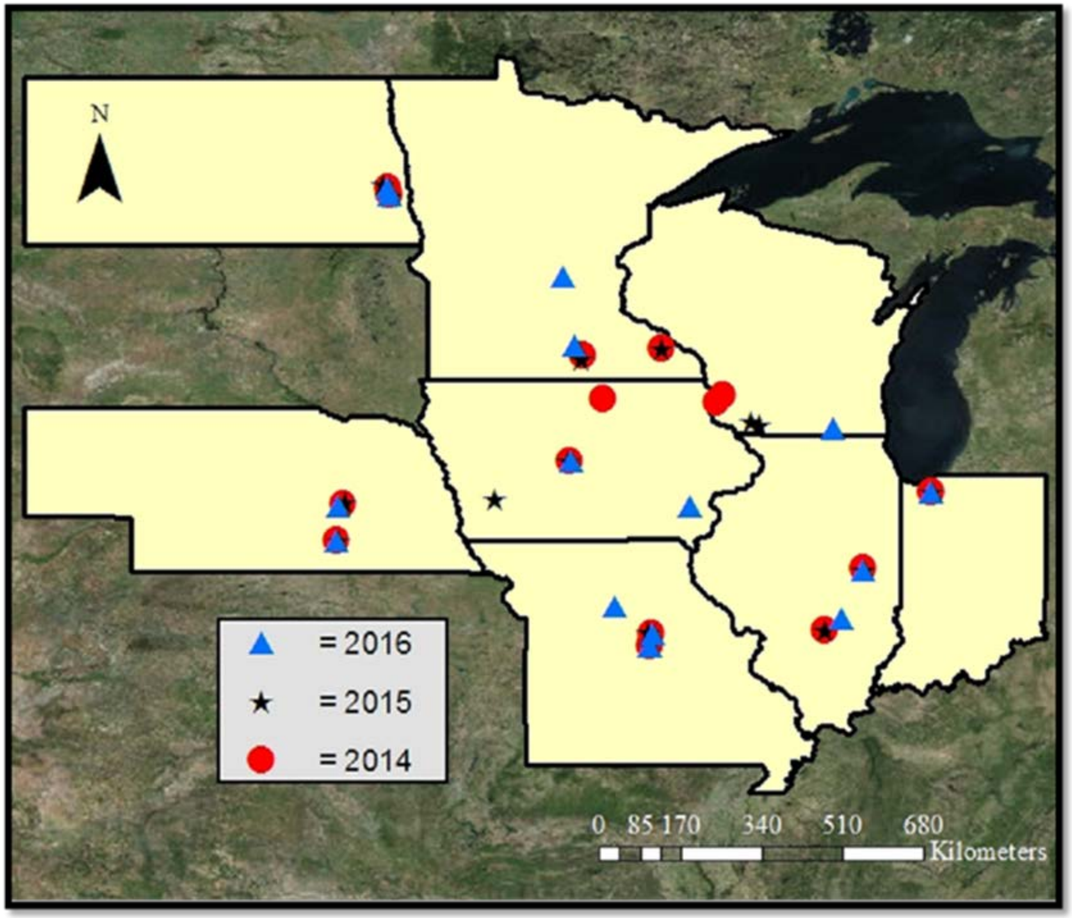

Figure 2.1. Field research sites were located within eight U.S. Midwest Corn Belt states (Iowa, Illinois, Indiana, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin). Each state contained two sites for each of the three growing seasons (2014 – 2016; Missouri had three sites for the 2016 growing season), totaling 49 sites.

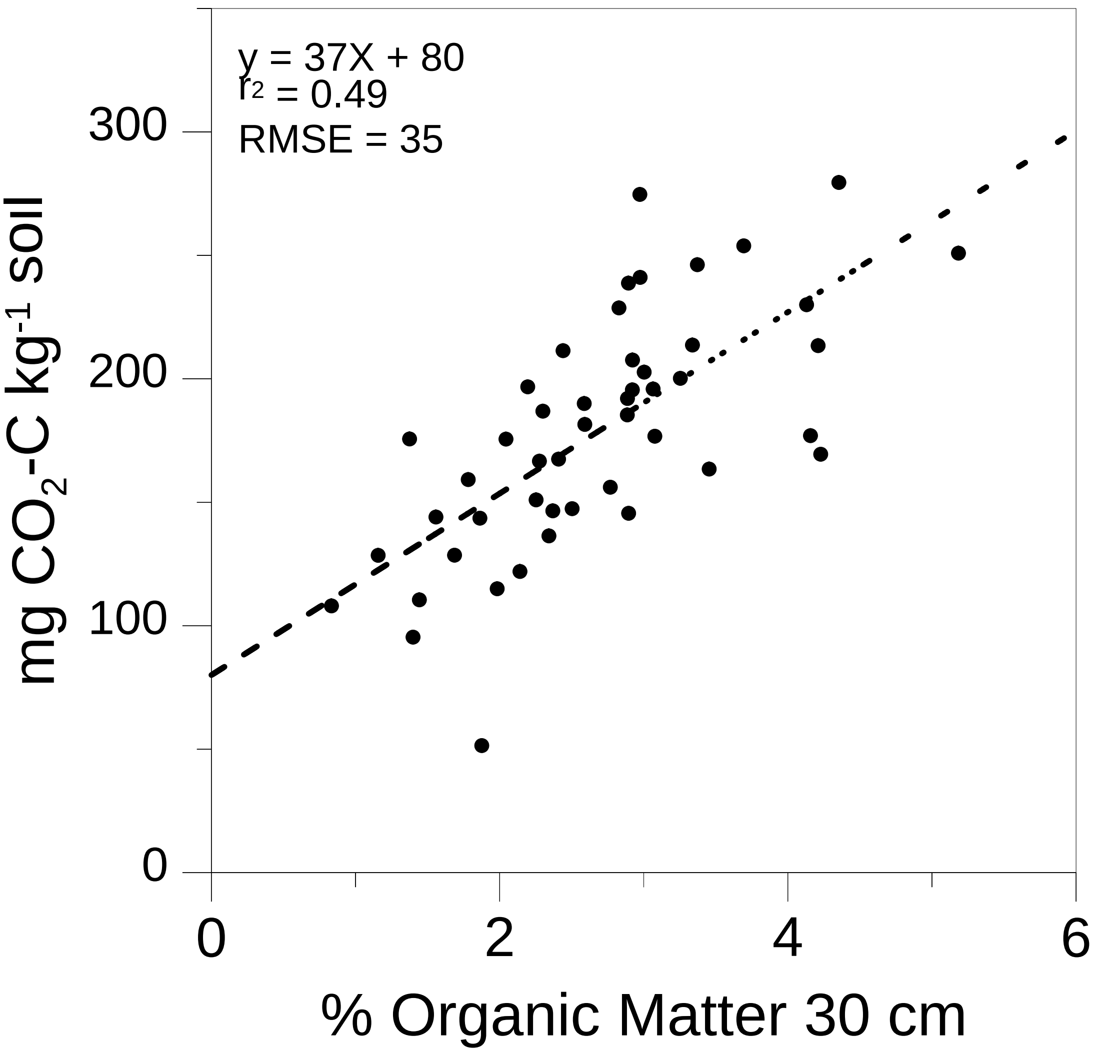

Figure 2.2. Analysis between organic matter in the top 30 cm of soil and the Cornell Soil Health Assessment soil respiration test. A significant positive relationship was found. As % organic matter increased soil respiration increased.

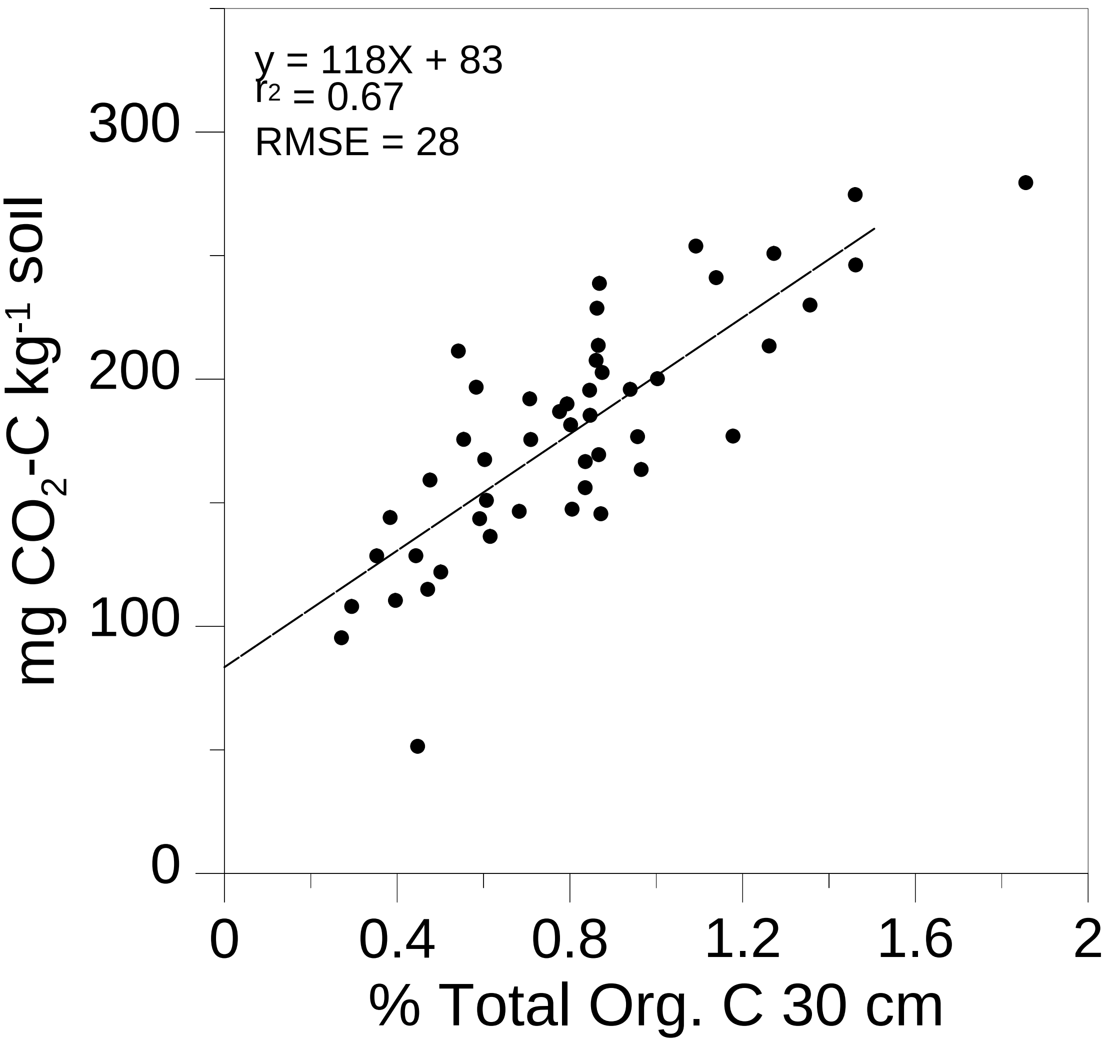

Figure 2.3. Analysis between total organic carbon in the first 30 cm of soil and the Cornell Soil Health Assessment soil respiration test (measured in mg CO_2-C kg^{-1} soil). Total organic carbon was found significantly related to soil respiration. This was not surprising. As labile C pool grows, soil microbial activity increases.

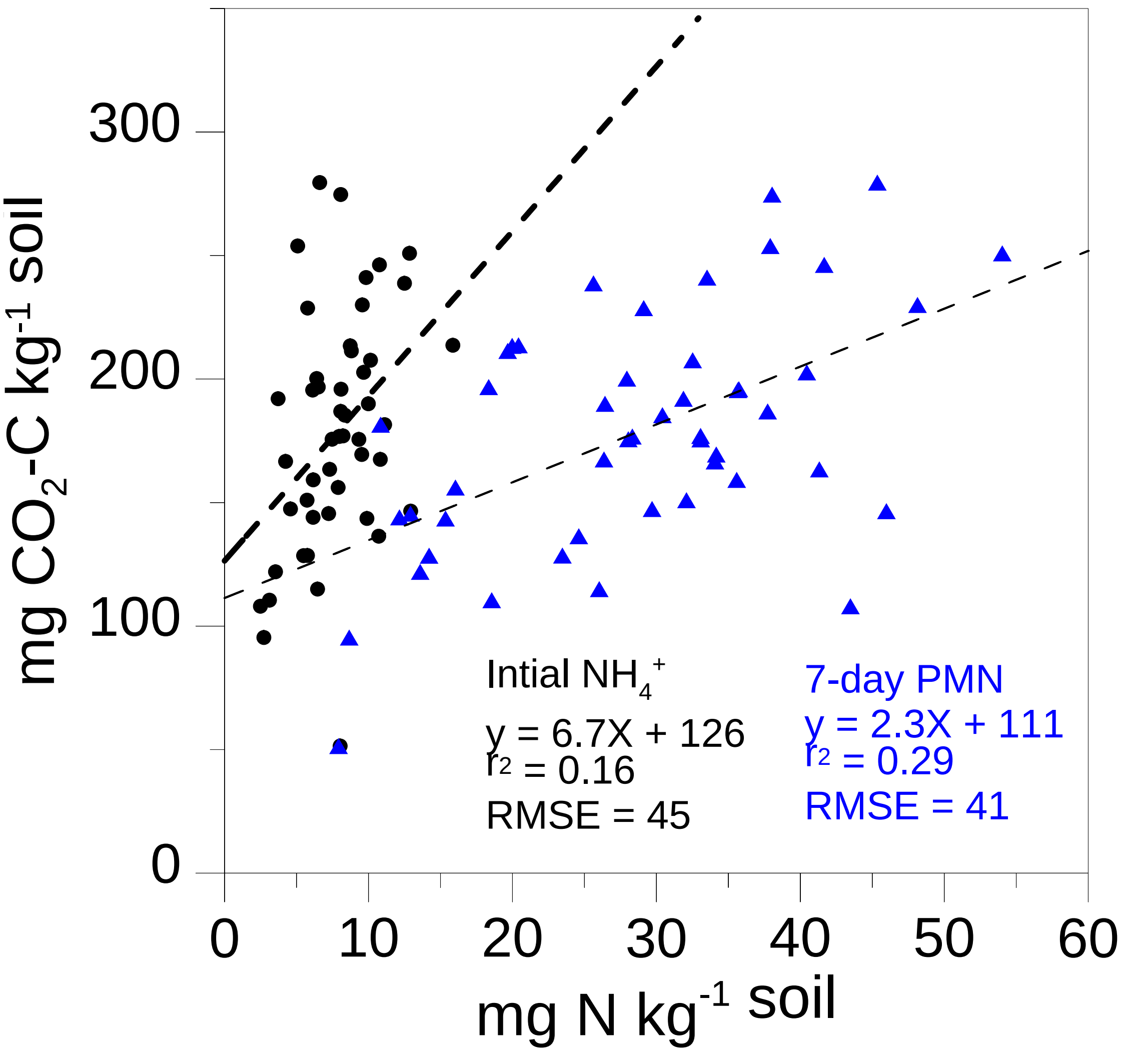

Figure 2.4. Analysis between initial NH_4^+-N (black dots) amounts and potentially mineralizable NH_4^+-N (7-day PMN; blue triangles) and the Cornell Soil Health Assessment soil respiration test (measured in mg CO_2-C kg^{-1} soil). Initial NH_4^+-N and the PMN test were found significantly related to soil respiration. The relationship between PMN and soil respiration was highly dependent on several factors such as N being immobilized by the recently activated soil microbes.

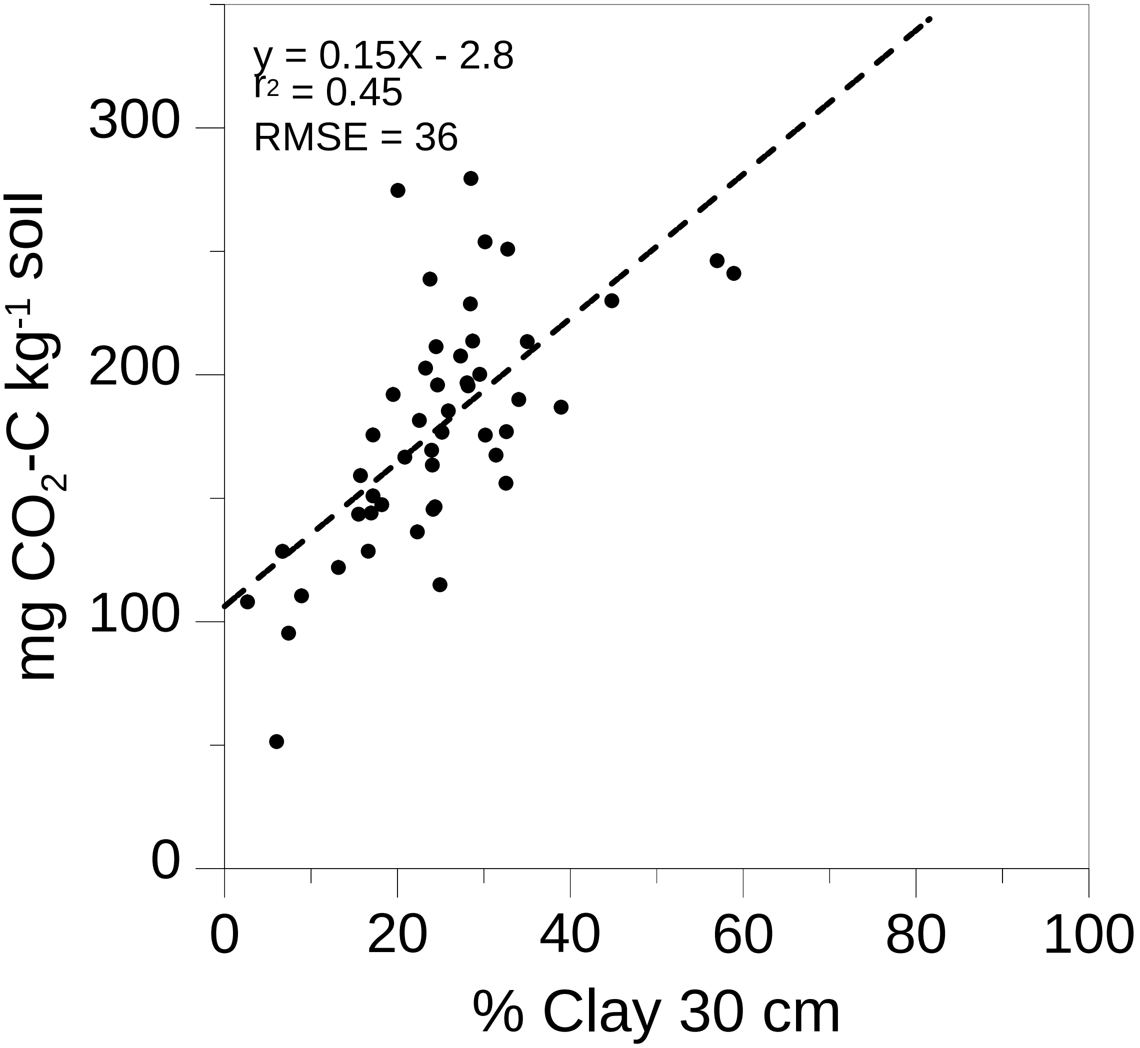

Figure 2.5. Analysis between % clay in the first 30 cm of soil and the Cornell Soil Health Assessment soil respiration test (measured in mg CO_2-C kg^{-1} soil). Clay in the first 30 cm of soil was found significantly related to soil respiration. This may partially be due to the sieve size. The 2 mm sieve size used in this analysis likely made C available that was otherwise protected by clay aggregates.

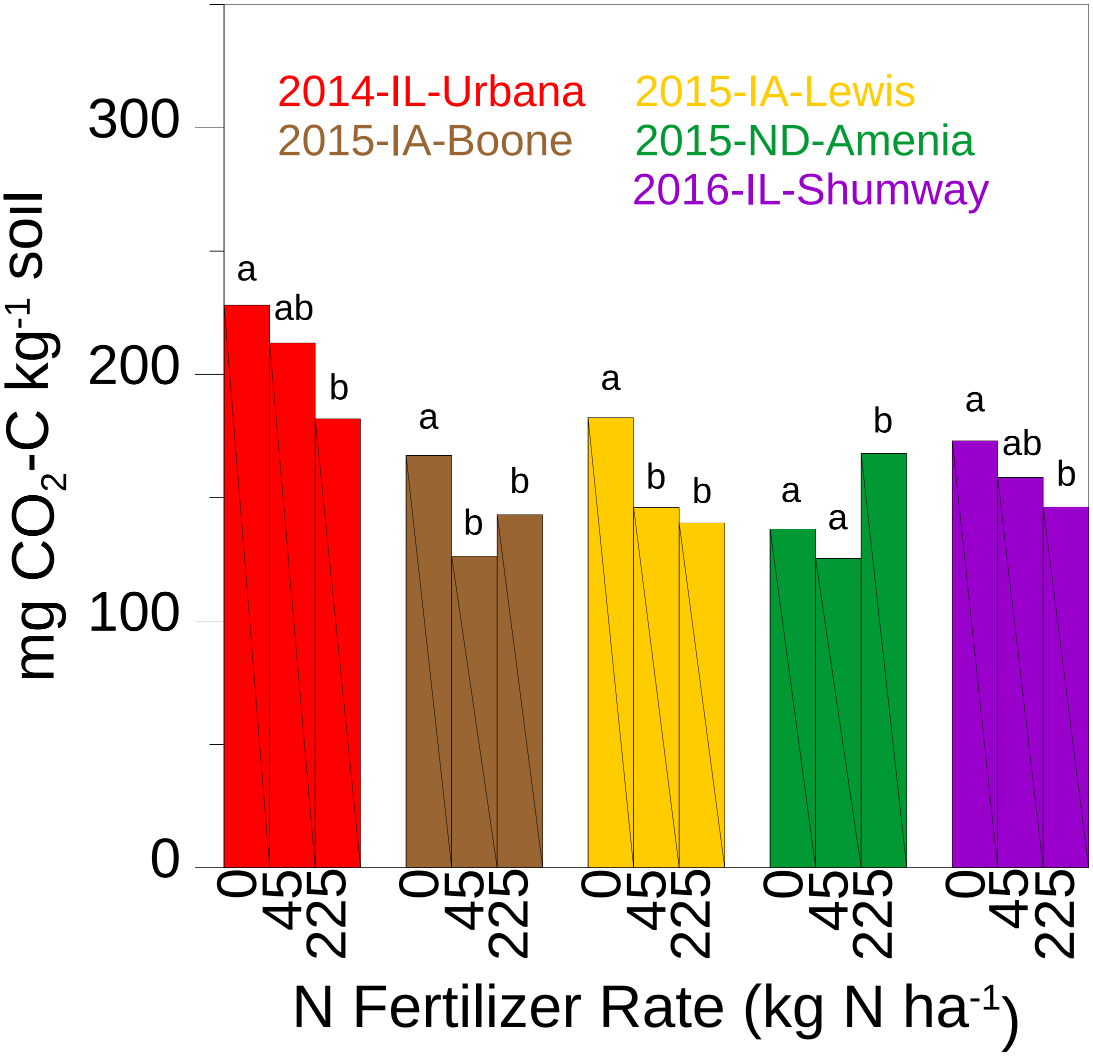

Figure 2.6. The relationship between increasing N fertilizer rate and soil respiration (measured in mg CO_2-C kg^{-1} soil). Following a within-site PROC GLM MANOVA analysis (SAS 9.2), soil respiration at five of the 49 site locations was found to be significantly different between added N fertilizer rates. Four of the five sites experienced decreasing soil respiration with increasing N fertilizer amount while one site experienced the opposite, increasing soil respiration with increasing fertilizer amount.

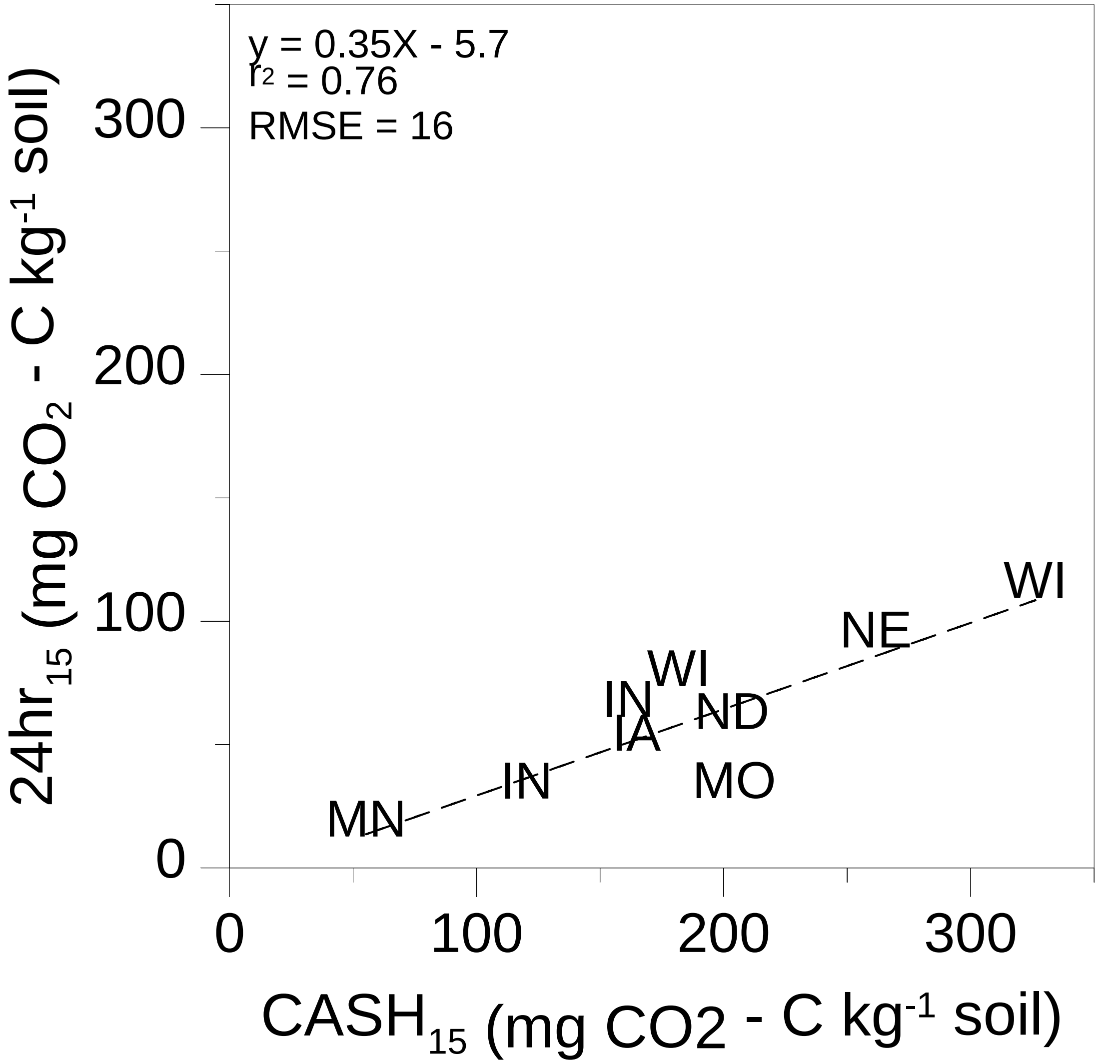

Figure 2.7. Relating soil respiration measurements in the top 15 cm of soil from the Solvita CO_2-Burst analysis ($24hr_{15}$) to the Cornell Soil Health Assessment soil respiration analysis ($CASH_{15}$). Soil samples were analyzed using the 24 hr method in the spring of 2016. Following two years of storage, soil respiration was again measured using the CASH method. The 24 hr and CASH soil respiration measurements were found significantly related. These results demonstrate soils with low respiration amounts prior to storage will have low respiration amounts following storage.

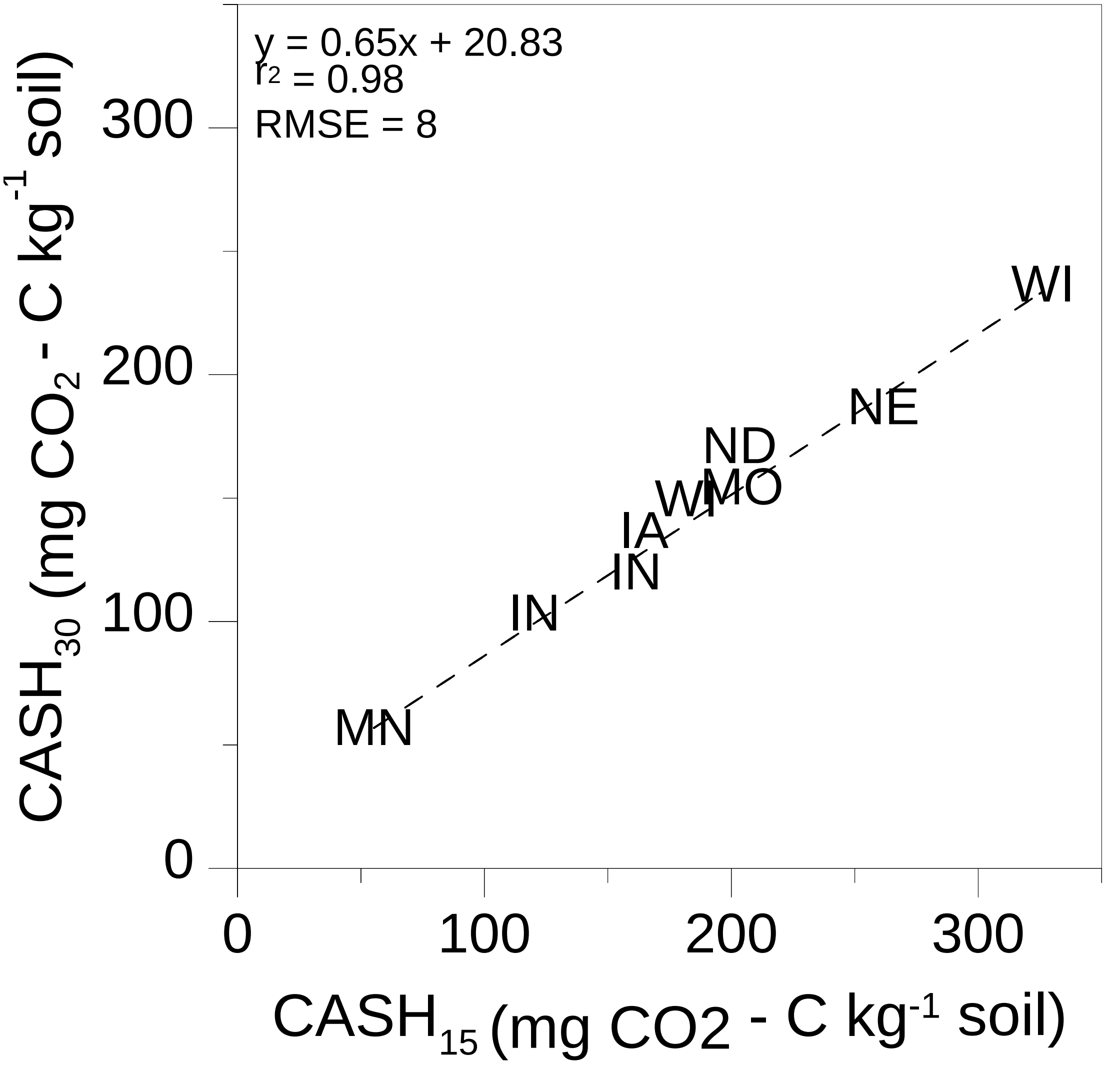

Figure 2.8. Comparing the Cornell Soil Health Assessment soil respiration test measurements from the 15 ($CASH_{15}$) and 30 ($CASH_{30}$) cm depths. The two depths were found significantly related. These results demonstrate that sampling down to 15 cm was sufficient.

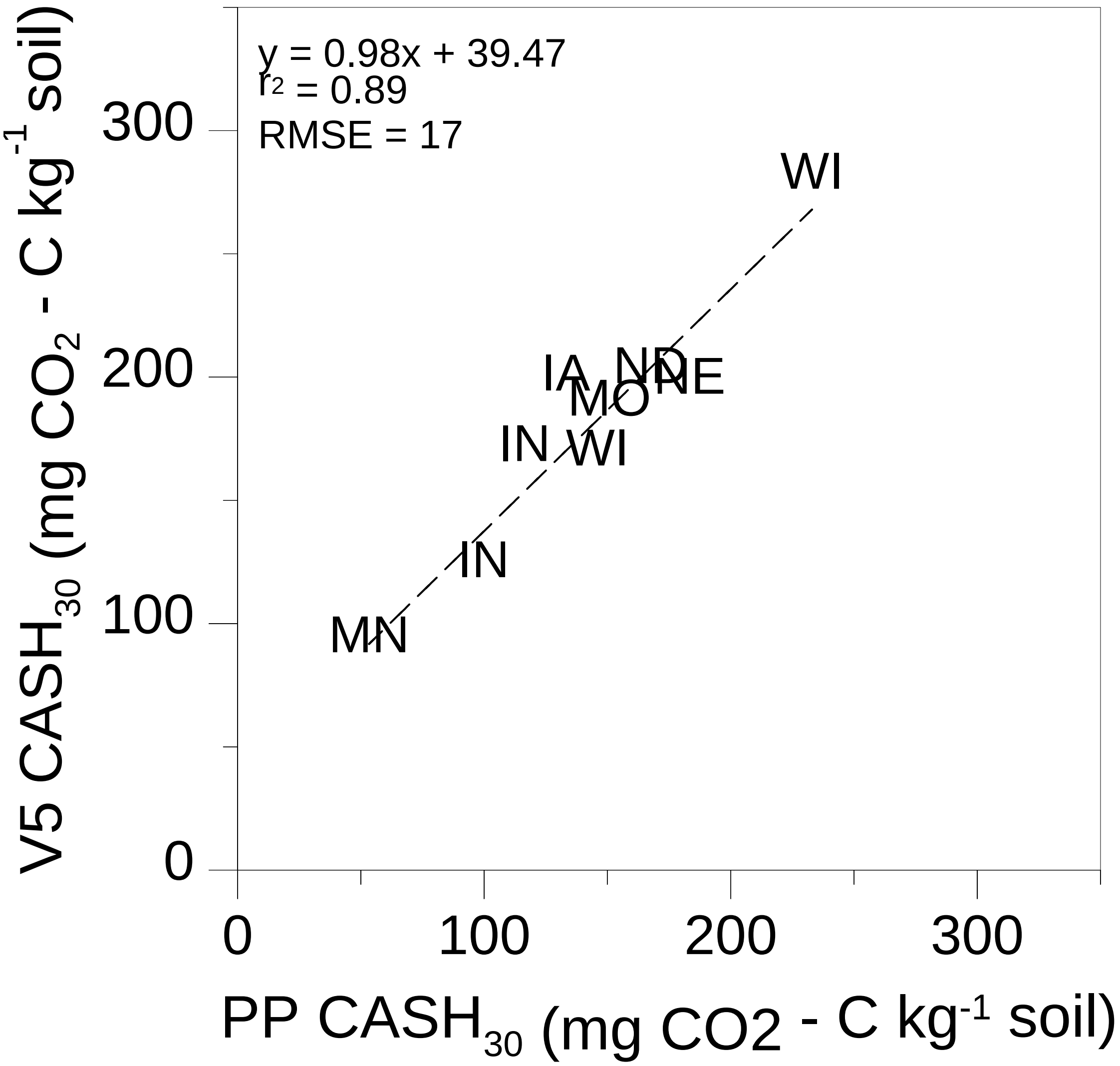

Figure 2.9. Comparing the Cornell Soil Health Assessment soil respiration test measurements, at the 30 cm depth, between the pre-plant (PP $CASH_{30}$) and V5 (V5 $CASH_{30}$) timings. Timings were found significantly related. Results suggested using pre-plant soil samples to estimate soil respiration later in the season was feasible and could help avoid busier times during the season.

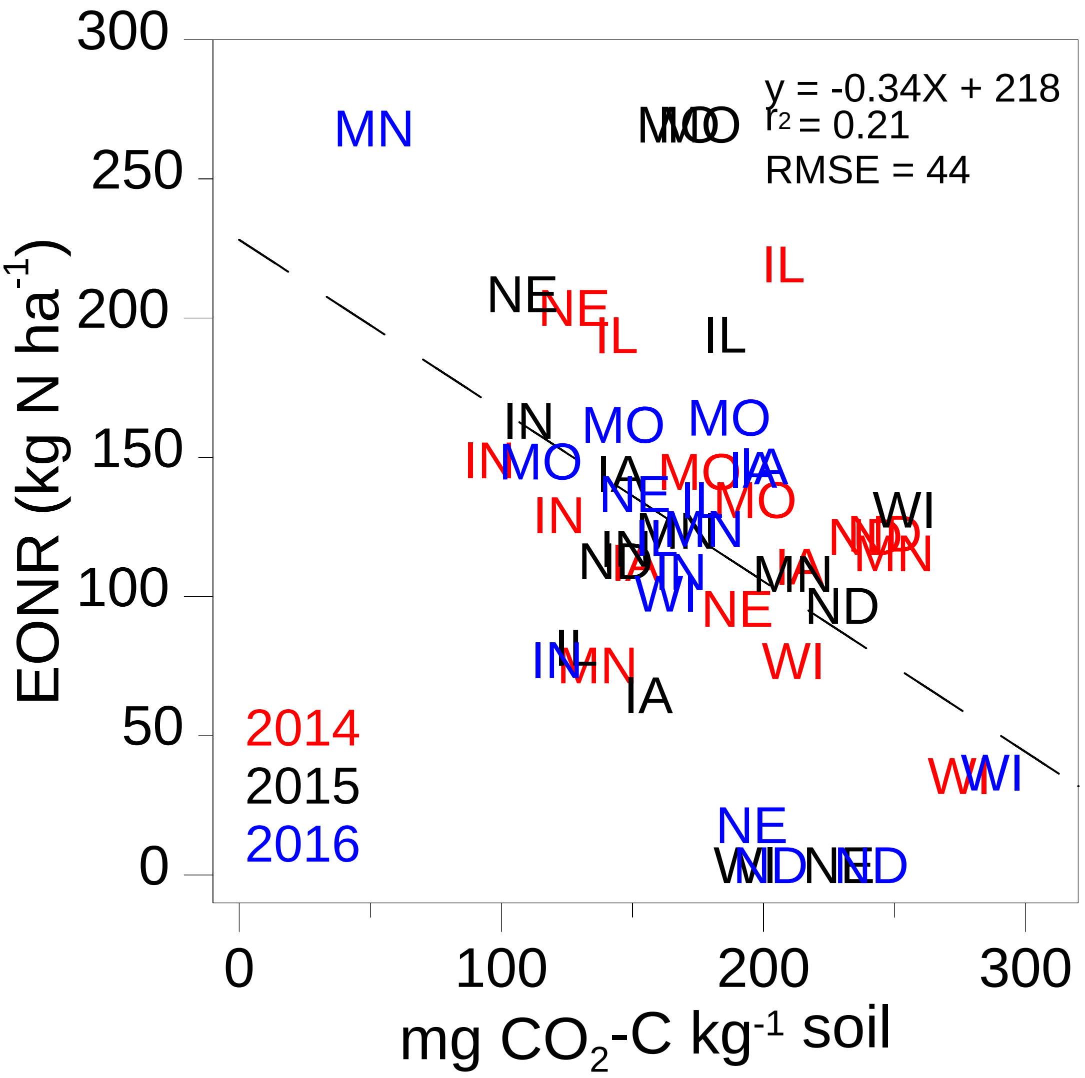

Figure 2.10. The Cornell Soil Health Assessment soil respiration test (measured in mg CO_2-C kg^{-1} soil) compared across three growing seasons and eight states (N = 49) to corn economical optimal N rate (EONR). A significant negative relationship was found between these two variables. Results suggest that as soil respiration increased, more soil N was made available for plant uptake decreasing the overall amount of inorganic N needed.

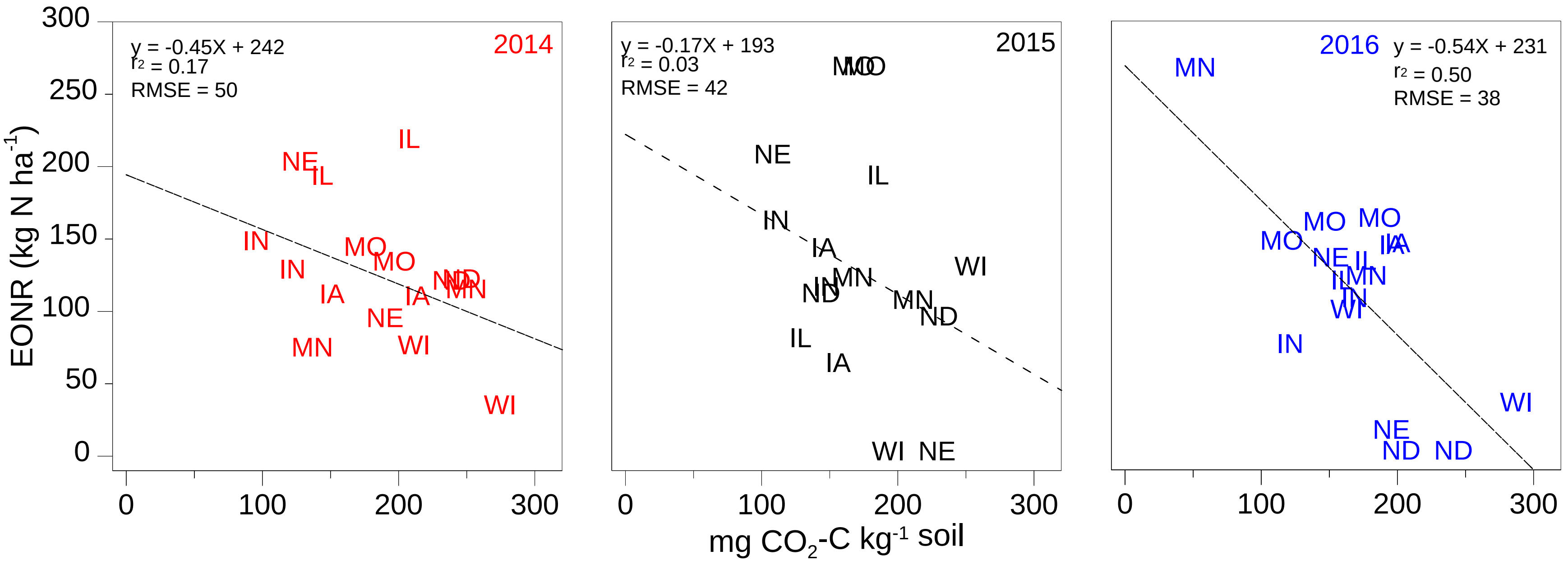

Figure 2.11. The Cornell Soil Health Assessment soil respiration burst test (measured in mg CO_2 – C kg^{-1} soil) compared to the economical optimal N rate (EONR) in corn, separated by growing season (2014 – 2016). The 2016 growing season was found most related to EONR. While this was an ideal growing season for microbial activity, it should be noted that if the Minnesota (MN) site in the top left corner of the graph was removed from the analysis the relationship between soil respiration and EONR would have become less significant.

Chapter 3: Using USDA-NRCS Hydrologic Soil Groups and Drainage Classifications to Estimate N Fertilizer Recommendations

3.1 Abstract

Nitrogen fertilizer recommendations in corn (Zea *mays* L.) that match the economical optimum N fertilizer rate (EONR) are imperative to increasing profitability and preventing environmental losses of N. However, processes influencing N in corn production (i.e. leaching and denitrification) are affected by soil and weather characteristics making it difficult to know when and how much N fertilizer to apply to match EONR. Following site delineation by USDA-NRCS defined hydrologic soil groups (HG) and drainage classifications the objective of this analysis was to determine which soil, weather, and canopy reflectance variables are best at estimating N fertilizer need. A total of 49 N response trials were conducted across eight U.S. Midwest Corn Belt states over three growing seasons (2014 – 2016). Two EONR values were calculated for each site. One for plots that received all N at-planting and another for those that received split-applied N. Measured and SSURGO soil variables, weather variables (collected from the time of planting to the time of side-dress), and canopy reflectance measurements (gathered at the V9 corn growth development stage) were linearly regressed against EONR values. Those found most significant were used to create HG-based N fertilizer recommendation models. The created models were within 34 kg N ha^{-1} of EONR 55% (at-planting) and 78% (side-dress) of the time and outperformed farmer chosen N fertilizer rates. These results demonstrate hydrologic soil group and drainage

classification could potentially aid in estimating N fertilizer recommendations. However, further model validation is needed.

3.2 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 economical optimal N rate (EONR). These practices help maintain profit while minimizing N lost to the environment. Commonly, N fertilizer amount is over-applied to ensure maximum yield, resulting in poor N use efficiency and environmental pollution (Tremblay et al., 2012; Schröder et al., 2000; Shanahan et al., 2008). But because of the spatial and temporal variability of soil and weather factors impacting the fate of soil N, determining EONR before or early in the growing season is difficult. Corn N uptake is negligible early in the growing season, and when uncertain weather conditions prevail year-to-year, producers are motivated to split-apply N fertilizer mid-season.

Historically, N fertilizer recommendations have been derived from expected grain yield (Blackmer et al., 1992; Gehl et al., 2005), but this fails to consider N response to soil and weather conditions for the year ahead. Soil and weather metrics have been related to corn N response (Xie et al., 2013, Tremblay et al., 2012). Furthermore, corn N response as measured by the yield increase with N fertilization is significantly related to EONR ($r^2 = 0.52$; Meisinger et al., 2008). Understanding weather and soil variability, and their relationship to crop response measurements can be used to improve N fertilizer recommendations and help prevent environmental losses of N.

Canopy reflectance sensors attempt to use the crop as a bioassay to assess variable N requirements as a result of spatial and temporal variability found within a specific field and time. These sensors capture plant N status by emitting visible and near infrared wavebands of light onto the crop canopy and then measure the amount reflected back (Shanahan et al., 2003). Comparing measured reflectance values between adequately-fertilized and N-deficient corn, coupled with an algorithm, allows for a calculated N fertilizer recommendation (Biggs et al., 2002; Kitchen et al., 2010). Such a diagnostic tool could aid in recommending the correct amount of N fertilizer applied to reach optimal yields (Scharf et al., 2002; Kitchen et al., 2010; Barker and Sawyer, 2010; Scharf et al., 2011). Financial benefits have been documented by using canopy sensors to synchronize the application of N fertilizer with corn N uptake. Fifty-five on-farm trials during 2004 to 2008 were conducted in Missouri where canopy sensing was used to inform top-dress N fertilizer applications (Scharf et al., 2011). Sensing N rates were compared to a fixed rate that producers' used on these same fields. Across all fields, canopy sensors increased partial grower profits by an average of \$42 ha^{-1} over producer rates. In another assessment over three differing soil areas conducted from 2004 to 2007 canopy sensor N fertilizer applications performed better than producer chosen N fertilizer applications on about half of 16 field-scale experiments (Kitchen et al., 2010). On average they found using canopy sensing generated a \$25 to \$50 ha^{-1} profit. However, recent studies comparing canopy sensor N fertilizer recommendations to EONR have not been promising. Across 49 site locations over three growing seasons, canopy sensor calculated N fertilizer rates were within 34 kg N ha^{-1} of EONR only about

30% of the time (Bean et al., 2018). Accounting for certain soil and weather properties may inform users when canopy sensor based N management is appropriate.

Spatial diversity of soil texture, soil organic matter (SOM), and plant available water (PAWC) across any given landscape combined with varying total rainfall, the evenness of rainfall, and temperature contribute to the complexities and fate of N in crops and the environment. Denitrification (the conversion of NO_3^- to $N0_x$ and N_2 gases) most often occurs in clayey textured soils experiencing anaerobic soil conditions from excessive rainfall and with 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 coarse textured soils (Power et al., 2001). Volatilization, (the loss of N through ammonia-NH_3 gas), 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. Research is needed to decide how these soil and weather variables can aid in making better N fertilizer recommendations.

Precipitation and temperature generally drive plant growth and influence soil conditions including soil microbial activity (Tremblay and Bélec, 2006), which ultimately influence corn yield. In years with above-average rainfall, corn has been generally found to respond more to applied 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, as well as by temperatures during July and August (Jeutong et al., 2000). The distribution or evenness of rainfall has also been found significant in describing corn yield responsiveness to N fertilizer, thus affecting yield (Shaw, 1964; Reeves et al., 1993; Tremblay et al., 2012). For example, frequent rainfall events in 51 studies were observed from 2006 to 2009 in several North American locations and were found to have large amounts of soil moisture early in the growing season that prompted N loss through denitrification and leaching, as well as increased the responsiveness to N fertilizer (Tremblay et al., 2012). Rainfall and temperature are widely accepted as variables directly impacting yield-limiting soil factors. These factors include oxygen levels, soil microbial activity, decomposition of organic matter (N mineralization), nutrient availability, plant-available water, and ultimately crop yield (Power et al., 2001; Tremblay, 2004; Tremblay and Bélec, 2006; Kyveryga et al., 2007; Shanahan et al., 2008; Tremblay et al., 2012).

Soil texture affects soil water flow, available N, plant-available water content (PAWC), the transportation and availability of ions (Schaetzl and Anderson, 2014), and crop yield (Zhu et al., 2009; Armstrong et al., 2009; Tremblay et al., 2012). While conflicting results exist, corn yield is generally greater on coarse-textured soils during wet years than during dry years. Also, corn yields tend to be greater on fine-textured soils during dry years than during wet years (Tremblay et al., 2011). Fifty-seven studies on smallholder farms in sub-Saharan Africa demonstrated the effect of soil texture on N fertilizer response. Nitrogen response was found to be greater on clay soils compared to loam or sandy soils (Chivenge et al., 2011). Similarly, in North America, finer textured soils were found to respond more to N fertilizer (Tremblay et al., 2012). Soil organic matter has also proven to be related to corn yield; soil organic matter makes up a small percentage of the total soil volume (<5%) but has a large effect on other soil properties (Sylvia et al., 2005). As SOM increases, soil aggregation improves, water infiltration rates rise and aeration increases. Collectively, these effects ultimately improve growing conditions.

Some of the above mentioned soil and weather interactions have been used by the USDA-NRCS to classify hydrologic soil groups (HG) and drainage classes. Each USDA-NRCS Soil Survey Geographical database (SSURGO) soil series is assigned a HG and drainage class (NRCS, 2007). 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 (NRCS, 2007). Soils that fall within the same HG are thought to respond similarly. 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 (Soil Survey Division Staff, 1993). When considering NO_3-N loss on a watershed scale, HG were found to be one of the most important factors in estimating NO_3-N movement and loss pathways (Blanchard and Lerch, 2000). In forested soils in southern Quebec, drainage class was significantly related to N transformation rates and internal N cycling (Ullah and Moore, 2009). On soils in North Carolina, and when analyzed by drainage class, the Illinois soil N test was found negatively related to EONR (Williams et al., 2007).

Most current publically available N fertilizer recommendation tools such as those based on yield goal (Stanford, 1973; Brown et al., 2004; Shapiro et al., 2008), pre-plant and pre-sidedress soil NO_3^- tests (Bundy et al., 1999; Franzen, 2010; Sawyer and

Mallarino, 2017), Maximum Return to Nitrogen (MRTN; Sawyer et al., 2006; Morris et al., 2018), and canopy reflectance (Kitchen et al., 2010; Dellinger et al., 2008; Scharf and Lory, 2009; Barker and Sawyer. 2010) do not use guideline subgroups based on soil or weather characteristics in the formulation of an N fertilizer recommendation. As described previously, using such soil and weather groupings has proven effective in determining the fate of N. Additionally, crop growth models including Maize-N (http://hybridmaize.unl.edu/maizen.shtml) simulate soil and crop processes in an attempt to estimate EONR. Varying success has been observed with these models (Setiyono et al., 2011; Thompson et al., 2015; Ransom et al., 2018). A recent study comparing 31 unique N recommendation tools, including all those mentioned above, was conducted across 49 different site locations in the US Midwest Corn Belt over three growing seasons (2014 – 2016). When compared to EONR, all N fertilizer recommendation tools evaluated had correlation coefficients < 0.20 (Ransom et al., 2018). Therefore, grouping field or site locations by HG and drainage class may aid in determining, for locations within each delineated group, the spatial and temporal variables most sensitive to estimating EONR.

The objectives of this research were to 1) determine by HG and drainage class which soil, weather, or canopy reflectance information best relates to EONR, 2) develop and evaluate N fertilizer recommendation models based on important variables found in objective one, and 3) compare the HG-based model and standard farmer practice N fertilizer recommendations.

3.3 Materials and Methods

3.3.1 Sites and Nitrogen Treatments

This research was conducted as part of 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 DuPont Pioneer (Kitchen et al., 2017). This project is commonly referred to as the, "Performance and Refinement of Nitrogen Fertilization Tools" project. The approach for this research was fundamental N fertilizer application response field-plot studies conducted with standardized protocols and methods across a wide range of soil and weather conditions. Yield and soil measurements from these plot studies provided the measurements needed to generate N recommendations and N response functions.

Forty-nine corn N response trials were conducted during 2014 to 2016 in eight Midwestern Corn Belt States. In each state, two sites ranging in productivity were selected for each growing season, giving six sites per state (Missouri had three in 2016; Figure 3.1). 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 hybrids (DuPont Pioneer, Johnstown, IA) found suitable for the selected sites within the region. Most research sites followed soybean, however five sites followed corn. There were five tile drained sites and eight irrigated sites. All but 14 sites received at least some form of tillage. Planting dates ranged from April 6 – May 23. Descriptions of management for all sites are presented in Table 3.1.

Sixteen different N application treatments, replicated four times (totaling 64 plots per site), were used in a randomized complete block design (Table 3.2). Nitrogen treatments were obtained using dry-prilled NH_4NO_3 fertilizer broadcast applied. The "at-planting" fertilizer was applied within 48 hours of initial planting while the side-dress fertilizer was applied between the V8 to V10 leaf stage. Treatment one was the non-fertilized control. Treatments 2 to 8 received all N at-planting in 45 kg N ha^{-1} increments from 45 to 315 kg N ha^{-1}, while treatments 9 to 14 received 45 kg N ha^{-1} at-planting and the rest at side-dress in 45 kg N ha^{-1} increments from 45 to 270 kg N ha^{-1}. Treatments 15 and 16 received 90 kg N ha^{-1} at-planting with the remaining N at side-dress. Plot dimensions were state and site dependent and were determined by the planting (planter width) and harvesting (combine width) equipment available, but the minimal plot harvest area was 18.6 m^2. Average size per site was 0.4 ha.

3.3.2 Canopy Sensor, Soil, and Weather Measurements

Reflectance measurements were collected using the RapidSCAN CS-45 Handheld Crop Sensor (Holland Scientific, Lincoln, NE) just prior to side-dress application (V8-V10 leaf stage). Manufacturer recommendations were followed during initial canopy sensor setup. The sensor was held approximately 60 cm above the row as the operator steadily walked approximately 4 kph alongside the row. Only plot rows used for yield measurements were sensed. The RapidSCAN CS-45 uses three different wavebands of light, red (670 nm, VIS), red edge (720 nm, RE), and near-infrared (780 nm, NIR) and were utilized in calculating indices tested in this study. Vegetative and sufficiency indices explored in this analysis include the Normalized Difference Vegetative Index (NDVI), the Normalized Difference Red-edge (NDRE), Inverse Simple Ratio (ISR), Inverse Simple Ratio Red-edge (ISR_{RE}), Chlorophyll Index (CI) and the Chlorophyll Index Red-edge (CI_{RE}). Calculations for each index listed above can be found in Bean et al 2018. Based on coefficient of determination and probability values, the ISR and NDRE vegetative and sufficiency indices were used for final regression analysis. Plots receiving 45 kg N ha^{-1} at-planting were considered target corn while plots that received 225 and 270 kg N ha^{-1} at-planting were averaged and used as N-reference corn.

Both measured soil and SSURGO data were gathered for all sites and years. Soil ECa surveys were used to guide site characterization soil sampling. Surveys were completed one to four weeks prior to planting using a Veris 3100 (Veris Technologies, Salina, KS). Sensing was performed on 4.5 m spacing travelling 5 kph across the plot area. Perpendicular passes were made through the plot area to aid in the creation of a post grid map in Surfer (Golden Software, Golden, CO). For soil characterization, two adjacent 1.2 m deep soil cores with a diameter of 4.76 cm were obtained from each of the four replications at each site using a Giddings Model #5-UV / MGSRPSUV (Giddings Machine Company, Windsor, CO). The location of both soil cores in each replication was determined using the soil ECa survey map performed just prior to sampling, such that core sites represented the range of soil differences within a site as observed by soil ECa. Both drilled cores were laid side-by-side and characterized and separated by horizon. One core was used to measure bulk density (BD) and soil moisture at sampling while the other was processed and sent to the University of Missouri Soil Health Assessment Center for additional analyses. Analyses included the following: particle size determination through the pipette method, cation exchange capacity (CEC), total carbon, total organic carbon, total inorganic carbon, soil organic matter (SOM), pH (salt and water), and bulk density (R. Burt and Soil Survey Staff, 2014). Amount of clay (i.e. % clay) was calculated by using the particle size determination (R. Burt and Soil Survey Staff, 2014; Nelson and Sommers, 1996). Plant Available Water Content was determined using the Saxton and Rawls formula (Saxton and Rawls, 2006). This equation uses measured sand and clay textural information along with SOM to determine soil water content at both the permanent wilting point and field capacity. The difference between the soil water content at field capacity and permanent wilting point results in PAWC. Following this analysis, the four cores from each site were averaged together to obtain site-level data.

The Cornell Soil Health Assessment (CASH) soil respiration test (Moebius-Clune et al., 2016) was used to determine soil biological activity through the output of CO_2 during a 4-day incubation period (Zibilske, 1994). The protocol requires air dried soil samples to be sieved to 8 mm, however the soils for this analysis were sieved to 2 mm. The 20 g soil samples were placed in pre-perforated aluminum weigh boats (nine pin holes in the bottom). Filter paper (No. 8) was placed at the bottom of a one pint, wide mouth, “Ball” brand Mason jar, the aluminum weigh boat containing the 20 g soil sample was placed on top of the filter paper. The trap assembly (pizza stool acting as pedestal was glued to the bottom of a 10 ml beaker) was placed in the aluminum weigh boat over top the soil sample. Using a pipette, 9 ml of 0.5 M potassium hydroxide (KOH) was placed in the 10 ml beaker. Immediately following, 7.5 ml of deionized water was added to the filter paper. The two piece Mason jar lid was then screwed on. One Mason jar with no soil (referred to as a blank) and one with reference soil were added for every 25 normal samples. The Mason jars were then placed in a jar rack to prevent disturbance over the 4-day incubation period. Further CASH protocol descriptions can be found in the Cornell Soil Health Assessment training manual (Moebius-Clune et al., 2016).

The SSURGO data for each site was obtained from the NRCS via the “Web Soil Survey” website and the “Soil Data Viewer” plug-in available in ArcMap (Esri, Redlands, CA). If more than one SSURGO mapping unit was assigned to the 0.4 ha research site, the most dominant SSURGO mapping unit was chosen. Soil variables collected from SSURGO included SOM, %clay, and PAWC. All soil variables considered, either measured or retrieved from SSRUGO, were depth-weighted to two intervals of 0-30cm and 0-60cm.

Each site’s weather data were collected using a HOBO U30 Automatic Weather Station (Onset Computer Corporation, Bourne, MA). Daily temperatures were used to calculate growing degree days (GDD) while daily precipitation (and irrigation), in conjunction with the Shannon Diversity Index (a measure of evenness; SDI) was used to calculate a measurement called abundant and well-distributed rainfall (AWDR; Tremblay et al., 2012). These variables were calculated using the equations below:

$$GDD = \frac{T_{Max}+T_{Min}}{2} - T_{Base} \qquad [1]$$

where T_{Max} = maximum daily temperature, T_{Min} = minimum daily temperature and T_{Base} = 10^0 C. All temperature values were measured in degrees Celsius (^{0} C).

$$SDI = \left[-\sum pi \frac{ln(pi)}{ln(n)}\right] \qquad [2]$$

where pi = daily rainfall/total precipitation and n = number of days in the specified time period being used.

$$AWDR = SDI \times Total\ Precipitation \qquad [3]$$

where precipitation and AWDR are measured in mm. Weather data used in these calculations were collected between the dates of planting and side-dress.

3.3.3 Site Delineation by Hydrologic Soil Group and Drainage Class

Prior to the HG classification, a number of different approaches for grouping the 49 site locations were explored. A few of these approaches included separating sites by low, medium, and high amounts of clay, depth of topsoil, % soil organic matter, pH, pre-plant and pre-sidedress NO_3^- concentrations, and relative yield to added N fertilizer. These various means of classification were explored based on their previously documented ability to estimate crop N need or the fate of N in agricultural cropping systems (Reuss et al., 1977; Andraski and Bundy, 2002; Tremblay et al., 2012; Morris et al., 2018). From this preliminary exploratory analysis, the HG and drainage class delineation method was identified as having the greatest potential for grouping the 49 sites of this research for further variable assessment and N fertilizer recommendation development.

Hydrologic soil group and drainage classification was gathered from the SSURGO database via Soil Web (University of California, Davis, CA). Initial site delineation was made by using HG classification. There are four total USDA-NRCS HGs (A,B, C, D) with group A having the least potential for runoff and group D having the highest potential. Seven total USDA-NRCS drainage classifications have been defined, however for this analysis sites were considered either poorly-drained (PD) or well-drained (WD). Further information on HG or drainage class is found in Tables 3.3 and 3.4. Initial site delineation was made by grouping sites that fell within HGs A and D. While HG A and D soils are vastly different, these soils are prone to N loss via leaching (HG A) or denitrification (HG D), and because both have a high propensity for N loss they were grouped together. Further delineation was made by grouping sites that were within HG B and then grouping sites that were within HG C. Final delineation was made by separating sites within HGs B and C by being either well- or poorly-drained (WD or PD; Figure 3.2). Site delineation using this method resulted in five groups (Figure 3.2).

3.3.4 Evaluation and Statistics

Data were analyzed using SAS version 9.2 (SAS Institute Inc., Cary, NC) on a site-level basis by delineated HG. An EONR [corn grain price, \$ 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 (split N treatments were applied with 45 kg N ha^{-1} at planting and the remainder applied at the V9 development stage as a side-dress; Kitchen et al., 2017). 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:

$$EONR = \frac{-b-(N{:}corn\ price)}{(2c)} \qquad [4]$$

where b and c = linear and quadratic response coefficients from optimized quadratic function. For evaluating HG-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 situations.

Proc REG linear regression ($p < 0.05$) was utilized for evaluating, by delineated HG group, EONR (both N fertilizer timings) as a function of soil (both depth intervals), canopy reflectance, and weather variables. Included were all two-way interactions between these variables. Due to the nature of applying all N fertilizer at-planting, there were no weather variables or V5 soil respiration tests used in the analysis of the at-planting EONR (Table 3.5). From the regression model producing the greatest probability significance (either single or two-way interaction variable) the intercept and coefficient values were used to generate N recommendation models by HG group.

The performance of each created model was evaluated by comparing the N recommendation to the site level EONR that was determined using the total season-long N application and to the Farmer’s N rate (FNR). The FNRs were collected from participating producers and research farm site-managers or principle investigators. These values are based on personal field-specific experience and likely incorporated yield goal and MRTN approaches. Model and FNR performance was based on root mean square error (RMSE) and the percentage of sites within 34 kg N ha^{-1} of EONR. This value is similar to what others have used for testing N recommendation tool performance (Sawyer, 2013; Laboski, 2014) and is similar to the economic-environmental threshold determined using this same dataset (Bandura, 2017).

The RMSE was calculated for each algorithm as follows:

$$RMSE = \sqrt{\frac{\sum(N_{Mod} - N_{EONR})^2}{n}} \qquad [5]$$

where N_{Mod} = the model N rate recommendation, N_{EONR} is the measured EONR, and *n* is the total number of site years.

3.4 Results and Discussion

Following site-delineation, a total of nine sites were in HGs A and D, 14 sites in HG B-WD, five sites in HG B-PD, six sites in HG C-WD, and 15 sites in HG C-PD. The most significantly related variables to EONR for both N timings are found in Table 3.6.

3.4.1 Variables Most Significantly Related to At-planting EONR

3.4.1.1 HGs A and D

There were no variables used in this analysis found significantly related to EONR for HGs A and D for the at-planting N application time. This is likely due to the complexity of predicting seasonal N need, at the time of planting, on two contrasting soils both of which respond to weather events differently and are highly prone to N loss. Without weather information estimating corn N response on these soils with this HG-based approach is not possible. Therefore, when applying all N fertilizer at-planting for these soils another recommendation method would need to be used.

3.4.1.2 HG B-WD

For HG B-WD sites, EONR decreased as soil organic matter increased in the first 30 cm of soil (Table 3.6; HG B-WD graph in Figure 3.3). This result suggests sites with greater amounts of SOM provided greater soil N, which led to a lesser amount of inorganic N fertilizer for EONR. The IN coarse textured sites and MO river bottom site with low SOM (top left-hand corner of HG B-WD graph in Figure 3.3), were several of those that required the most amount of inorganic N fertilizer. Three of the WI sites with greater amounts of SOM (bottom right-hand corner of HG B-WD graph in Figure 3.3), were those that needed the least amount of inorganic N fertilizer.

While the main agronomic explanation for the relationship found is greater N mineralization with higher SOM, other soil properties and behavior are enhanced as

SOM increases, even though it makes up a small percentage of the total soil volume. Roughly 20 – 80% of the cation exchange capacity is determined by SOM. The products of SOM decomposition promote soil aggregation ultimately increasing the amount of water-stable aggregates. This allows for better infiltration, aeration, and root growth development (Sylvia et al., 2005). These characteristics help buffer against extreme weather conditions by storing soil water (Sylvia et al., 2005), which in turn allows for sustained biological activity and therefore conditions for N mineralization.

3.4.1.3 HGs B-PD and C-WD

A similar soil interaction was found for HG B-PD and HG C-WD (HG B-PD and HG C-WD graphs in Figure 3.3). For HG B-PD a positive interaction between PAWC and SOM (60 cm) best explained EONR, while for HG C-WD a positive interaction between clay and SOM (30 cm) best explained EONR. One explanation of this outcome for the sites of these groups are that since these soils are either poorly-drained or have low saturated hydraulic conductivity (K_{SAT}) values they were likely to have experienced anaerobic conditions during portions of the growing season. With increasing SOM and PAWC or clay, water movement through the soil profile becomes more stagnant. These properties result in soils staying wetter longer after precipitation events. In years with inadequate or interspersed rainfall these characteristics can be associated with improved crop yields, since crop water stress is dominant and soil water storage from these soils is relatively better. For this research, this outcome was not observed because the corn crop during the growing seasons included in this study was not drought stressed (Kitchen et al., 2017). However, when rainfall exceeds crop N needs for these soils, anaerobic conditions may exist and substantial inorganic N loss through denitrification can occur (Blevins et al., 1996). Comparing sites with similar SDI and precipitation values reveals the effect these three soil characteristics had on EONR. For example, the 2014 IN and IL sites had similar SDI and precipitation values following planting. However, the IN site had less PAWC allowing for better soil drainage, creating a more aerobic environment for microbial activity and ultimately greater N mineralization. Likewise, when comparing the two 2015 WI sites in HG C-WD (HG C-WD graph in Figure 3.3), two sites that were within 13 km of each other, it is evident increasing clay and/or SOM content led to an increase in EONR. These two sites had nearly identical SDI and precipitation values. The site that was 0 EONR in WI (Belmont) had 10% less clay and 1% less SOM. A possible explanation is that this site was not as susceptible to anaerobic conditions causing N loss, and/or had greater N mineralization.

3.4.1.4 HG C-PD

Within HG C-PD, variation in EONR was best related to total C (30 cm). This was the weakest relationship observed (HG C-PD graph in Figure 3.3). As the amount of total C increased, the N fertilizer needed to reach EONR decreased. As discussed previously relative to SOM, here soil C provides an energy source for soil microbes allowing for the mineralization of N. This property also was related to soil bulk density, a property important for promoting root growth (Weil and Brady, 2017). As total C increased, bulk density decreased. Although considered poorly drained, sites in HG C-PD with lower bulk densities (1.1 - 1.3 g cm^{-3}) and higher total C content (i.e., ND sites in bottom right-hand corner of the HG C-PD graph in Figure 3.3) were potentially less susceptible to N loss and/or greater N mineralization due to greater soil aeration conditions. Sites with higher bulk densities (1.3- 1.6 g cm^{-3}) and less total C (i.e., MO sites in the top left-hand corner of the HG C-PD graph in Figure 3.3) are most susceptible to N loss ultimately being more responsive to added N fertilizer. Interestingly, soils within this group had the largest range in EONR (>150 kg N ha^{-1}), suggesting the need to have N fertilizer recommendation tools for this group with greater flexibility to these soil conditions.

3.4.2 Variables Most Significantly Related to Side-dress EONR

3.4.2.1 HGs A and D

For side-dress applications for the combined HGs A and D, soil properties were not helpful in explaining variation in EONR, but weather information was. From weather variables SDI was most significantly related to EONR (HGs A and D graph in Figure 3.4). As SDI approached one (precipitation events are more evenly distributed) the amount of N fertilizer needed to reach EONR increased. The relationship was fairly strong for 8 of the 9 sites in this group, the 2016 IL Shumway site being the exception. Were this IL site removed, the regression coefficient of determination for this group would increase from 0.54 to 0.85 (discussed more below).

As previously documented, the evenness of precipitation can influence N uptake, mineralization, leaching, and denitrification (Tremblay et al., 2012). Hydrologic soil group A contains coarse textured soils (>90% sand) with high saturated hydraulic conductivity rates (K_{SAT}) and low runoff potential. Hydrologic soil group D contains soils that are high in clay content (>50%) with low K_{SAT} rates and high surface runoff potential. Therefore, more evenly distributed precipitation events from the time of planting to side-dress allowed these soils to stay wet longer ultimately increasing the potential for N loss via leaching and denitrification. Others comparing SDI to N response have found similar results (Tremblay et al., 2012; Kablan et al., 2017). While SDI from the time of planting to the time of side-dress was considered for this analysis, it was weather following side-dress that largely influenced the 2016 IL Shumway site. This site had similar soil characteristics as the 2014 and 2015 IL sites. However, the Shumway site received 15.6 cm of rain during the two weeks leading up to the silking reproductive stage (R1). In contrast, the 2014 and 2015 IL sites received approximately 3-4 cm of rain during this same 2-week period. As others have reported, corn is most sensitive to stress at this period due to pollination and fertilization (Abendroth et al., 2011). Stress during this period can greatly reduce kernel number (Abendroth et al., 2011). The timely rainfall at this site likely reduced stress and helped the corn achieve better N use efficiency compared to the other IL sites that received substantially less rainfall during this same time period in 2014 and 2015. Nonetheless, these results demonstrate that the relationship between SDI and EONR helps in estimating an in-season N fertilizer recommendation for soils found within HGs A and D.

3.4.2.2 HG B-WD

For HG B-WD, EONR was most related to soil respiration (HG B-WD graph in Figure 3.4). The negative relationship observed 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 microbial activity became more abundant, resulting in less need for inorganic N fertilizer to reach EONR. Not surprisingly, the coarse-textured IN sites (HG B-WD graph in Figure 3.4) with little organic matter (0.8 and 1.4 %, respectively) and lower PAWC had the lowest soil respiration and therefore the highest amount of inorganic N fertilizer required to reach EONR. Oppositely, two of the WI sites (classified as either loam or silt loam) with greater amounts of organic matter (3.5 and 4.4 %, respectively) and plant available water had the highest soil respiration and therefore the lowest amount of inorganic N fertilizer required to reach EONR.

Soil microbial activity is largely dependent on soil temperature and moisture (Linn and Doran, 1984; Howard and Howard, 1993; Davidson and Janssens, 2006). Nitrifying bacteria are aerobic requiring oxygen to make NO_2^--N and NO_3-N and therefore favor well-drained soils (Weil and Brady, 2017). Soils within HG B-WD seem to have been buffered against extreme temperature and moisture events preventing leaching and denitrification, ultimately creating a good environment for microbial activity. Results from chapter two of this dissertation support this claim. When compared by year soil respiration was found better related to EONR for the 2016 growing season ($r^2 = 0.50$) than the 2014 and 2015 growing seasons ($r^2 < 0.17$).

However, HG B-WD contains sites from all three growing seasons. Therefore, the sites within this group are buffered against year-to-year variations in weather allowing soil respiration measurements to more accurately estimate EONR.

3.4.2.3 HGs B-PD and C-WD

For both HG B-PD (clay in top 60 cm) and HG C-WD (clay in top 30 cm) EONR was related to the interaction between SDI and clay. With both, as this interaction increased, so did EONR, indicating that as either clay or SDI increased, the amount of inorganic N fertilizer required to reach EONR increased (HG B-PD and HG C-WD graphs in Figure 3.4). These sites were characterized with soil and weather factors such as poor drainage (wet at shallow depths during a large portion of the growing season), a shallow water table, nearly continuous rainfall, or increasing clay amounts (relative to HG B-WD soils). Such conditions lead to a lack of oxygen in the root zone, forcing facultative anaerobes to use the oxygen in NO_3-N as electron acceptors, whereby transforming soluble inorganic N into gaseous forms that easily release into the atmosphere (denitrification). Higher clay content as found in soils with pronounced argillic horizons magnifies the relationships described above because these horizons often are associated with inhibited infiltration, and thus ponding after significant precipitation events. These results are similar to those found by others. An analysis on 51 sites across North America revealed corn N response was greater on fine-textured soils than on medium-textured soils. Corn yields increased to added N fertilizer by a factor of 1.6 on medium textured soils but by a factor of 2.7 on fine-textured soils (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).

3.4.2.4 HG C-PD

For HG C-PD, EONR increased as the interaction between SDI and SSURGO-PAWC (60 cm) increased (HG C-PD graph in Figure 3.4). With the exception of HG D, soils within HG C-PD have the greatest amount of clay, the lowest K_{SAT} (0.36-3.6 cm hr^{-1}), likely have a restrictive layer or shallow water table, and experience long periods of standing water due to high episodic rainfall during the growing season. During dry years or years of more intermittent rainfall these characteristics may be beneficial. This is evident by comparing the 2016 North Dakota (ND) sites (bottom left-hand corner in the HG C-PD graph of Figure 3.4) with the ND sites in 2014 and 2015 (middle of the HG C-PD graph of Figure 3.4). The SDI at the 2016 sites was 0.53 while the SDI measurements at the 2014 and 2015 sites were between 0.63 – 0.68. With more interspersed rainfall during 2016, the high clay content and PAWC likely allowed for an increase in available soil N through mineralization, while the more evenly distributed rainfall of 2014 and 2015 likely created anaerobic conditions promoting N loss through denitrification (as described previously). This conclusion was also seen by Yost et al. (2018). Similarly, the 2015 Missouri site (MO; top right-hand corner of HG C-PD graph in Figure 3.4), a site adjacent to the Missouri River, had a near-surface elevated water table due to extended high water in the river from extreme rainfall events up river. Therefore, the soil profile was saturated for a prolonged period of time during the growing season leading to N loss. This MO site required a high N rate to reach EONR (270 kg N ha^{-1}).

3.4.2.5 Canopy Sensors

As stated previously, canopy reflectance was one of the variables explored in this analysis and vegetative and sufficiency indices were found significantly related to EONR for HGs C-WD and C-PD (totaling 21 of the 49 site locations). However, using the HG-based approach the relationship between canopy reflectance and EONR could not be agronomically explained. For example, as the indices analyzed increased or approached "1.0" the amount of N fertilizer needed to reach EONR increased. This is contrary to what others have observed (Scharf and Lory, 2009). The inverse was expected namely as N-deficient corn canopy reflectance mirrored that of the adequately fertilized corn (at the V9 growth development stage) a lesser amount of N fertilizer would be required to reach EONR. Coupled with a canopy sensor algorithm, such as the University of Missouri algorithm (Scharf et al., 2011; Bean et al., 2018), the observed relationship would lead to a negative correlation between actual and algorithm-estimated EONR. Meaning, as the algorithm recommended more N fertilizer, the opposite would be needed. Therefore, due to this relationship no canopy reflectance variable for these HG-based groups were used further.

3.4.3 Model Performance

Using the models reported in Table 3.6 and illustrated in Figures 3.3 and 3.4, N fertilizer recommendations were applied to these same 49 sites and contrasted with actual EONR. Though doing this utilizes the same data for both developing and testing, it is only an initial evaluation to view how this procedure impacted all sites across the different HG-based models. Certainly additional validation is needed. This comparison is summarized graphically in Figure 3.5. Sites on or near the 1:1 diagonal line are those in which the HG-based model N fertilizer recommendations performed reasonably well for making N fertilizer recommendations. Sites below or above the 1:1 line represent recommendations that under- or over-estimated inorganic N fertilizer need, respectively. Sites within the yellow shaded region were found to be within 34 kg N ha^{-1} of EONR. The dashed linear fit line represents the regression between HG model recommendations and EONR. For comparison, a similar figure is provided for FNR (Figure 3.6).

The at-planting HG-based model was mediocre at estimating EONR. The sites in HG A and D (9 total sites) are not included in this analysis because no variable was found significantly related to EONR. A total of 22 of the 40 remaining sites (55%) were within 34 kg N ha^{-1} of EONR. The at-planting HG-based model was able to predict 50% of the N needed as represented by the end-of-season calculated EONR (Figure 3.5) suggesting dull sensitivity to variations in EONR. When observing the five ND sites, which are all considered HG C-PD, the range in model N recommendations was 60 to 125 kg N ha^{-1}. However, the range in EONR for these sites was 0 to 175 kg N ha^{-1}. The difference between model and EONR ranges was due to year-to-year temporal variability. Furthermore, the 2015 and 2016 HG C-PD Illinois (IL) sites (top right-hand corner of the at-planting graph in Figure 3.5) were < 200 m apart but their EONR values were more than 60 kg N ha^{-1} different. This could in part be explained by an additional 21 cm of rainfall received during the 2016 growing season. This demonstrates the importance of the interaction between soil and weather variables and the risk of applying all N fertilizer at planting.

The side-dress HG-based model performed well at estimating EONR. A total of 39 of the 49 sites (78%) were within 34 kg N ha^{-1} of EONR. The side-dress HG-based model was able to predict 75% of the N needed as represented by the end-of-season calculated EONR (the side-dress graph in Figure 3.5) suggesting better sensitivity to variations in EONR. However, for some sites the HG approach did not accurately estimate side-dress N need. For example, the model N recommendation over-estimated N need for one of the 2016 Illinois (IL) sites. This site was included in HG D (top center in Figure 3.5) where SDI was found to explain the most variation in EONR (HGs A and D graph in Figure 3.5). While classified as HG D, timely rainfall aided in preventing N stress and promoting soil microbial activity lowering the need for added N. Additionally, the HG-based model under-estimated N need for one of the 2015 MO site (top right hand corner of side-dress graph in Figure 3.5). As discussed previously, this site experienced surface water seepage due to non-local rainfall events upriver. Simply, the model could not account for these events. An additional analysis comparing the performance of 31 N recommendation tools on this same dataset by Ransom et al (2018) revealed tools designed to capture site-specific soil and weather were poorly related to EONR. From this analysis, no N recommendation tool resulted in greater than 39 or 43% of the recommendations being within 30 kg N ha^{-1} of EONR for the at-planting and side-dress N timings, respectively. 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 difficult (Scharf et al., 2005; Scharf and Lory, 2009; Morris et al., 2018).

Both HG-based at-planting and side-dress models (Figure 3.5) performed better than the FNR (Figure 3.6). For FNR, a total of 38 and 41 % percent of the sites were within 34 kg N ha^{-1} of EONR for the at-planting and side-dress N fertilizer timings, respectively. With near zero coefficient of determinations and slopes as represented by the dashed linear fit lines, demonstrates the lack of the FNR methods to predict corn N need for these study sites. Across all years, sites, and N times the FNR over-estimated EONR by approximately 30 kg N ha^{-1}.

3.5 Conclusions

Unlike side-dress N management, when applying all N fertilizer at-planting weather and other in-season variables are unavailable in determining an N recommendation. Therefore, only soil variables collected before planting were used in the at-planting N time analysis. However, several similarities were found between the side-dress and at-planting analyses. For example, no soil variables were significantly related to EONR for HG A and D. Soil organic matter explained the most variation in EONR for HG B-WD soils. Further study reveals % SOM and soil respiration (HG B-WD for the side-dress N time) were positively correlated. At both N timings and for HGs B-PD and C-WD, soil variables (i.e. % clay, % SOM, and PAWC) that impact the flow of soil water were found significantly related to EONR. Hydrologic soil group C-PD had the greatest variation in EONR and the weakest relationship between EONR and collected variables for both the side-dress and at-planting N timings. Some of the delineated HG groups had as few as five observations for model development, which is perhaps too few for confidently relying on them for N fertilizer recommendations.

For the side-dress N time, SDI was found significantly related to EONR for all but HG B-WD. As SDI approached “1” more inorganic N was needed to reach EONR. For three of the five delineated groups the interaction between SDI and either clay or SSURGO-PAWC explained the most variation in EONR. Variation in EONR for sites within HG B-WD was best explained by V5 soil respiration. The soil characteristics of these sites are such that they are buffered against extreme weather conditions making EONR sensitive to changes in soil respiration.

The side-dress HG-based N recommendation model performed best demonstrating the importance of weather from the time of planting to the time of side-dress in determining the correct amount of N fertilizer to apply. However, both side-dress and at-planting N models outperformed the FNR. While 41 and 38 % of the sites were within 34 kg N ha^{-1} of EONR for the side-dress and at-planting N times, the FNR was not sensitive to changes in EONR. These results suggest using HG and drainage classifications could aid in determining the amount of in-organic N fertilizer needed to reach EONR. However, the models created in this analysis need to be validated using outside N response datasets to ensure the relationships observed here are useable. Therefore, further research is needed to explore these relationships.

Also, canopy reflectance vegetative and sufficiency indices included in this analysis were found significantly related to EONR for two HG-based groups. However, our observations between canopy reflectance indices and EONR were contrary to those of others and warrants further investigation. Therefore, these relationships were not used in the formation of the HG-based N fertilizer recommendation models.

3.6 Bibliography

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR 1009. Iowa State University Extension, Ames, IA.

Andraski, T.W., and L.G. Bundy. 2002. Using the pre-sidedress soil nitrate test and organic nitrogen crediting to improve corn nitrogen recommendations. Agron. J. 94:1411-1418. doi:10.2134/agronj2002.1411

Armstrong R.D., J. Fitzpatrick, M.A. Rab, P.D. Fisher, M. Abuzar, P.D. Fisher, and G.J. O'Leary. 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 Pasture Sci. 60:870-884. doi:10.1071/CP08349

Bandura, C.J. 2017. Agronomic and environmental evaluation of nitrogen rate and timing for Midwestern corn production. MS. theses., Univ. of Wisconsin, Madison.

Barker, D.W., and J.E. Sawyer. 2010. Using active canopy sensors to quantify corn nitrogen stress and nitrogen application rate. Agron. J. 102:964-971. doi:10.2134/agronj2010.0004

Bean, G.M., N.R. Kitchen, J.J Camberato, R.B. Ferguson, F.G. Fernandez, D.W. Franzen, C.A.M. Laboski, E.D. Nafziger, J.E. Sawyer, P.C. Scharf, J. Schepers, and J.S. Shanahan. 2018. Improving an active-optical reflectance sensor algorithm using soil and weather information. Agron. J. 110:1-11. doi:10.2134/agronj2017.12.0733

Biggs, G.L., T.M. Blackmer, T.H. Demetriades-Shah, K.H. Holland, J.S. Schepers, and J.H. Wurm. 2002. Method and apparatus for real-time determination and application of nitrogen fertilizer using rapid, non-destructive crop canopy measurements. U.S. Patent 6,393,927. Date issued: 28 May.

Blackmer, A.M., G.D. Binford, T. Morris, and B. Meese. 1992 Effects of rates of nitrogen fertilization on corn yields, nitrogen losses from soils, and energy consumption. p. 2.1-2.6. In 1991 progress report of the intergrated farm management demonstration program. Iowa State Univ. Pm-1467

Blanchard, P.E. and R.N. Lerch. 2000. Watershed vulnerability ot losses of agriucltural chemicals: Interactions of chemistry, hydrology, and land-use. Environ. Sci. Technol. 34(16) pp 3315-3322. doi:10.1021/es991115+

Blevins D.W., D.H. Wilkison, B.P. Kelly, and S.R. Silva. 1996. Movement of nitrate fertilizer to glacial till and runoff from a claypan soil. J. Envir. Qual. 25:584-593. doi:10.2134/jeq1996.00472425002500030026x

Brown, J.R., D.K. Crocker, J.D. Garret, R.D. Hanson, J.A. Lory, M.V. Nathan, P.C. Scharf, and H.N. Wheaton. 2004. Soil test interpretations and recommendation handbook. Univ. of Missouri, College of Agric., Div. of Plant Sci., Columbia. aes.missouri.edu/pfcs/soiltest.pd. (Accessed 23 May 2016).

Bundy, L.G., D.T. Walters, and A.E. Olness. 1999. Evaluation of soil nitrate tests for predicting corn nitrogen response in the North Central region. North Central Region. Urbana, 51

Chivenge, P., B. Vanlauwe, and J. Six. 2011. Does the combined application of organic and mineral nutrient sources infuence maize productivity? Plant Soil 342: 1-30. doi:10.1007/s11104-010-0626-5

Davidson, E.A., and L.A. Janssens. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440: 165-173. doi: 10.1038/nature04514

Dellinger, A.E., J.S. Schmidt, and D.B. Beegle. 2008. Developing nitrogen fertilizer recommendations for corn using an active sensor. Agron. J. 100:1546-1552.

Franzen, D.W. 2010. North Dakota fertilizer recommendation: Tables and equations. https://www.ag.ndsu.edu/publications/crops/north-dakota-fertilizer-recommendation-tables-and-equations. (Accessed 23 May 2016).

Gehl, R.J., L.D. Maddux, and W.B. Gordon, and J.P. Schmidt. 2005. Corn yield response to nitrgoen rate and timing in sandy irrigated soils. Agron. J. 97:1230-1238. doi:10.2134/agronj2004.0303

Howard, D.M.., and P.J.A. Howard. 1993. Relationships between CO_2 evolution moisture content and temperature for a range of soils types. Soil Biol. Biochem. 25:1537-1546. doi:10.1016/0038-0717(93)90008-Y

Jeutong, F., K.M. Eskridge, W.J. Waltman, and O.S. Smith. 2000. Comparison of bioclimatic indices for prediction of maize yields. Crop Sci. 40: 1612-1617

Kablan, L.A., V. Chabot, A. Mailloux, M. Bouchard, D. Fontaine, and T. Bruulsema. 2017. Variability in corn yield response to nitrogen fertilizer in Eastern Canada. Agron. J. 109:2231-2242. doi:10.2134/agronj2016.09.0511

Kitchen, N.R., K.A. Sudduth, S.T. Drummond, P.C. Scharf, H.L. Palm, D.F. Roberts, and E.D. Vories. 2010. Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. Agron. J. 102:71-84. doi:10.2134/agronj2009.0114

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

Kyveryga P.M., A.M. Blackmer, and F. Morris. 2007. Alternative benchmarks for economically optimum rates of nitrogen fertilization for corn. Agron. J. 99:1057-1065. doi: 10.2134/agronj2006.0340

Laboski, C.A.M., J.J. Camberato, J.E. Sawyer. 2014. Evaluation of adapt-N in the Corn Belt. In: Proceedings North Central Extension-Industry Soil Fertility Conference, Des Moines, IA. 19-20 Nov. 2014. International Plant Nutrition Inst. Brookings, SD. p. 60-67.

Linn, D.M., and J.W. Doran. 1984. Effet of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci. Soc. Am. J. 48: 1267-1272. doi: 10.2136/sssaj1984.03615995004800060013x

Meisinger, J.J., J.S. Schepers, and W.R. Raun. 2008. Nitrogen in agricultural systems. p.563-612. American Society of Agronomny, Crop Science Society of America, Soil Science Society of America, 677 S. Segoe Rd., Madison, WI. doi: 10.2134/agronmonofr49.c14

Ma, B.L., T.Y. Wu, N. Tremblay, W. Dean, N.B. McLaughlin, M.J. Morrison, and G. Stewart. 2010. On-Farm assessment of the amount and timing of nitrogen fertilizer on ammonia volatilization. Agron. J. 102:134-144. doi:10.2134/agronj2009.0021

Moebius-Clune, B.N., D.J. Moebius-Clune, B.K. Gugino, O.J. Idowu, R.R. Schindelbeck, A.J. Ristow,…G.S. Abawi. 2016. Comprehensive Assessment of Soil Health: The Cornell Framework Manual (3.1 ed.).

Morris, T.F., T.S. Murrell, D.B. Beegle, J.J. Camberato, R.B. Ferguson, J. Grove, Q. Ketterings, P.M. Kyveryga, C.A.M. Laboski, J.M. Mcgrath, J.J. Meisinger, J. Melkonian, B.N. Moebius-clune, E.D. Nafziger, D. Osmond, J.E. Sawyer, P.C. Scharf, W. Smith, J.T. Spargo, H.M. van Es, and H. Yang. 2017. Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. Agron. J. 110:1–137.

Natural Resource Conservation Service (NRCS). 2007. Chapter 7 Hydrologic Soil Groups. Part 630 Hydrology National Engineering Handbook.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In: Methods of Soil Analysis, Part 2, 2nd ed., A.L. Page et al., Ed. Agronomy. 9:961-1010. Am. Soc. of Agron., Inc. Madison, WI.

Power J.F., R. Weise, and D. Flowerday. 2001. Managing farming systems for nitrate control: A research review from managemetn systems evaluation areas. Environ. Quality J. 30: 1866-1880

Ransom, C.J., N.R. Kitchen, J.J. Camberato, P.R. Carter, R.B. Ferguson, F. G. Fernandez. D.W. Franzen, C.A.M. Laboski, E.D. Nafziger, J.E. Sawyer, P.C. Scharf, and J.F. Shanahan. 2018. Corn nitrogen rate recommendation tools' performance across eight U.S. Midwest Corn Belt States. PhD. Dissertation. Univ. of Missouri, Columbia.

Reeves, D.W., C.W. Wood, and J.T. Touchton. 1993. Timing nitrogen applications for cornin a winter legume conservation-tillage system. Agron. J. 85:98-106

Reuss, J.O., P.N. Soltanpour, and A.E. Ludwick. 1977. Sampling distribution of nitrates in irrigated fields. Agron. J. 69:588-592. doi:10.2134/agronj1977.00021962006900040016x

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

Sawyer, J.E. Comparison of the MRTN and Adapt-N derived N rates for corn. 2013. In: Preceedings North Central Extension-Industry Soil Fertility Conference, Des Moines, IA. 20-21 Nov. 2013. International Plant Nutrition Inst., Brookings, SD. p. 7-14

Sawyer, J.E., and A.P. Mallarino, 2017. Use of the Late-Spring Soil Nitrate Test in Iowa Corn Production. https://store.extension.iastate.edu/Product/5259. (accessed 5 May 2018)

Saxton, K.E., and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70:1569-1578. doi:10.2136/sssaj2005.0117

Schaetzl, R., and S. Anderson. 2014 Soils Genesis and Geomorphology. 6th printing. Cambridge University Press, Cambridge, United Kingdom

Scharf, P.C. and J.A. Lory. 2002. Calibrating corn color from aerial photographs to predict sidedress nitrogen need. Agron. J. 94:397-404.

Scharf, P.C., N.R. Kitchen, K.A. Sudduth, J.G. Davis, V.C. Hubbard, and J.A. Lory. 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. Agron. J. 97:452-461. doi: 10.2134/agronj2005.0452

Scharf, P.C. and J.A. Lory. 2009. Calibrating reflectance measurements to predict optimal sidedress nitrogen rate for corn. Agron. J. 101:615-625. doi:10.2134/agronj2008.0111

Scharf P. C., D. K. Shannon, H. L. Palm, K. A. Sudduth, S. T. Drummond, N. R. Kitchen, L. J. Mueller, V. C. Hubbard, L. F. Oliveira. 2011. Sensor-based nitrogen application out-performed producer-chosen rates for corn in on-farm demonstrations. Agron. J. 103: 1683-1691. doi:10.2134/agronj2011.0164

Schröder, J.J., J.J. Neeteson, O. Oenema, and P.C. Stuik. 2000. Does the crop or soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crops Res. 66:151-164. doi:10.1016/S0378-42909(00)000-72-1

Setiyono, T.D., H. Yang, D.T. Walters, A. Dobermann, R.B. Ferguson, D.F. Roberts et al. 2011. Maize-N: A decision tool for nitrogen management in maize. Agron. J. 10:1276-1283. doi:10.2134/agronj2011.0053

Shahandeh H., A.L. Wright, and F.M. Hons. 2011. Use of soil nitrogen parameters and texture for spatially-variable nitrogen fertilization. Precis. Agric. 12: 146-163. doi:10.1007/s11119-010-9163-8

Shanahan, J.F.. K. Holland, J.S. Shepers, D.D. Francis, M.R. Schlemmer, and R. Caldwell. 2003.Use of crp reflectance sensors to assess corn leaf chlorophyll content. p. 135-150. In T. VanToai et al. (ed.) Digital imaging and spectral techniques: Applications to precision agriculture and crop physiology. ASA Spec. Publ. 66. ASA, CSSA, and SSSA, Madison, WI.

Shanahan, J.F., N.R. Kitchen, W.R. Raun, and J.S. Schepers. 2008. Responsive in-season nitrogen management for cerals. Comput. Electron. Agric. 61:51-62. doi:10.1016/j.compag.2007.06.006

Shaw, L.H. 1964. The effect of wether on agricultural output: A look at the methodology. J. Farm Econ. 46:218-230

Shapiro, C.A., R.B. Ferguson, G.W. Hergert, C.S. Wortmann, and D.T. Walters. 2008. Fertilizer suggestions for corn. University of Nebraska NebGuide EC117.

Soil Survey Staff, 2014. Kellogg Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 5.0. R. Burt and Soil Survey Staff (ed.). U.S. Department of Agriculture, Natural Resources Conservation Service.

Stanford, G. 1973. Rationale for optimum nitrogen fertilization in corn production. J. of Environ. Qual. 2:159-166.

Sylvia, D.M., J.J. Fuhrmann, P.G. Hartel., and D.A. Zuberer. Principles and Applications of Soil Microbiology. 2005. 2nd Ed. Prentice Hall, Upper Saddle River, New Jersey

Thompson, L.J., R.B. Ferguson, N.Kitchen, D.W. Franzen, M. Mamo, H. Yang, and J.S. Schepers. 2015. Model and sensor-based recommendation approaches for in-season nitrogen management in corn. Agron. J. 107:2020-2030

Tremblay, N., 2004. Determining nitrogen requirements from crops characteristics: benefits and challenges. Recent res. Dev. Agron. Hortic. 1:157-182

Tremblay, N., and C. Belec. 2006. Adapting nitrogen fertilization to unpredictable seasonal conditions with the least impact on the environment. Hort-Technology 16:408-412

Tremblay, N., M.Y. Bouroubi, B. Panneton, S. Guillaume, and P. Vigneault. 2011. Guidelines for in-season nitrogen application for maize (Zea mays L.) based on soil and terrain properties. Field Crops Res. 122:273-283. doi:10.1016/j.fcr.2011.04.008

Tremblay N., Y. M. Bouroubi, C. Belec, R. W. Mullen, N. R. Kitchen, W. E. Thomason, S. Ebelhar, D. B. Mengel, W. R. Raun, D. D. Francis, E. D. Vories, and I. O. Monasterio. 2012. Corn response to nitrogen is influenced by soil texture and weather. Agron. J. 104:1658-1671. doi: 10.2134/agronj2012.0184

Ullah, S. and T.R. Moore. 2009. Soil drainage and vegetation controls of nitrogen transformation rates in forest soils, southern Quebec. J. Geophys. Res. Biogen. doi:10.1029/2008jg000824

Weil, R.R., and N.C. Brady. 2017. Nature and property of soils. The 15th edition. Upper Saddle River, NJ. Prentice Hall.

Williams, J.D., C.R. Cozier, J.G. White, R.W. Heiniger, R.R. Sripada, and D.A. Crouse. 2007. Illinois soil nitrogen test predicts southeastern US corn economic optimum nitrogen rates. Soil Sci. Soc. Am J. 71:735-744. doi:10.2136/sssaj2006.0135

Xie M., N. Tremblay, G. Tremblay, G. Bourgeois, M.Y. Bouroubi, and Z. Wei. 2013. Weather effects on corn response to in-season nitrogen rates. Can, J. Plant Sci. 93:407-417. doi:10.4141/CJPS2012-145

Yamoah C.F., G.E. Varvel, C. Francis, and W. Waltman. 1998. Weather and management impact on crop yield variability in rotations. J. Prod. Agric. 11: 219-225. doi: 10.2134/jpa1998.0219

Yost, M., K. Veum, N.R. Kitchen, J. Camberato, P. Carter, R. Ferguson, F. Fernandez, D. Franzen, C. Laboski, E. Nafziger, and J. Sawyer. 2018. Evaluation of the Haney Soil Health Nutrient Tool for corn nitrogen recommendations across eight Midwest states. J. Soil and Water Conserv. Soc.

Zibilske, L.M. 1994. Carbon mineralization. In: Weaver RW, Angle JS, Bottomley PS 9eds) Methods of Soil Analysis, Part 2. Microbiological and Biochemical Properties. Soil Sci. Soc. Am., Madison WI, pp 835-864

Zhu, Q., J.P. Schmidt, H.S. Lin, and R.P. Sripada. 2009. Hydropedological processes and their implications for nitrogen availability to corn. Geoderma 154:111-122. doi:10.1016/J.geoderma.2009.10.004

3.7 Tables and Figures

Table 3.1. Management description for the 49 sites for the 2014 – 2016 growing seasons. Each of the eight participating states chose two contrasting locations with varying productivity.

Year	State	Site	Productivity	Previous Crop	Tiled	Irrigated	Tillage†	Hybrid	Seed Rate	Row Space	Plant Date
									Seeds ha^{-1}	cm	
2014	IA	Ames	L	SB	No	No	FC	P0987AMX	86,450	76	7 May
2014	IA	Mas	H	SB	No	No	FC	P1498AM	85,215	76	9 May
2014	IL	Brown	L	SB	No	No	SP FC/ F deep ripped	P1498AM	86,450	76	24 Apr
2014	IL	Urbana	H	SB	No	No	FC / F deep ripped	P0987AMX	86,450	76	25 Apr
2014	IN	Loam	H	SB	No	No	FC	P0987AMX	80,275	76	19 May
2014	IN	Sand	L	SB	No	No	No-till	P0987AMX	80,275	76	19 May
2014	MN	New	H	SB	No	No	F FC/ SP FC	P0157AMX	87,685	76	21 May
2014	MN	Charles	L	SB	No	No	Vertical-till	P0157AMX	85,215	76	16 May
2014	MO	Bay	L	SB	No	No	FC	P1498AM	86,450	76	2 May
2014	MO	Troth	H	SB	No	No	FC	P1498AM	86,450	76	2 May
2014	ND	Amenia	H	Corn	Yes	No	No-till	P9188AMX	83,980	56	23 May
2014	ND	Durbin	L	Corn	No	No	No-till	P9188AMX	83,980	56	23 May
2014	NE	Brandes	L	SB	No	Yes	F chisel/ SP FC	P1151HR	86,450	76	19 Apr
2014	NE	SCAL	H	SB	No	Yes	F chisel/ SP FC	P1151HR	83,980	76	7 May
2014	WI	Waz	L	SB	No	No	No-till	P0987AMX	90,155	76	7 May

2014	WI	Steuben	H	SB	No	No	No-till	P0987AMX	93,119	76	6 May
2015	IA	Boone	L	SB	No	No	FC	P0987AMX	86,450	76	18 May
2015	IA	Lewis	H	SB	No	No	FC	P1498AM	85,215	76	29 Apr
2015	IL	Brown2	L	SB	No	No	SP FC/ F deep ripped	P1498AM	86,450	76	28 Apr
2015	IL	Urbana2	H	SB	No	No	FC / F deep ripped	P0987AMX	86,450	76	23 Apr
2015	IN	Loam2	H	SB	No	No	FC	P0987AMX	80,275	76	29 Apr
2015	IN	Sand2	L	SB	No	No	No-till	P0987AMX	80,275	76	29 Apr
2015	MN	New2	H	SB	No	No	F FC/ SP FC	P0157AMX	87,685	76	18 Apr
2015	MN	Charles2	L	SB	No	No	Vertical-till	P0157AMX	85,215	76	1 May
2015	MO	Lonetree	L	SB	No	No	FC	P1498AM	86,450	76	17 Apr
2015	MO	Troth2	H	SB	No	No	FC	P1498AM	86,450	76	14 Apr
2015	ND	Amenia2	H	Corn	Yes	No	No-till	P9188AMX	83,980	56	24 Apr
2015	ND	Durbin2	L	Corn	No	No	No-till	P9188AMX	83,980	56	24 Apr
2015	NE	Brandes2	L	SB	No	Yes	F chisel/ SP FC	P1151HR	86,450	76	19 Apr
2015	NE	SCAL2	H	SB	No	Yes	F chisel/ SP FC	P1151HR	83,980	76	24 Apr
2015	WI	Belmont	L	SB	No	No	No-till	P0987AMX	90,155	76	4 May
2015	WI	Darling	H	SB	No	No	No-till	P0987AMX	93,119	76	4 May
2016	IA	Crawford	H	SB	Yes	No	Chisel	P1197AMXT	86450	76	26 Apr
2016	IA	Story	L	SB	Yes	No	Chisel	P1197AMXT	86450	76	12 May
2016	IL	Shumway	L	SB	No	No	FC/ Vertical-till	P1197AM	79040	76	25 Apr
2016	IL	Urbana	H	SB	No	No	FC	P1197AMXT	88920	76	19 Apr

2016	IN	Loam	H	SB	No	No	F Rip/ SP FC	P1197AMXT	80275	76	20 May
2016	IN	Sand	L	SB	No	No	F Chisel / SP FC	P1197AMXT	80275	76	20 May
2016	MN	Becker	L	SB	No	Yes	SP Chisel/ Rip	P0157AMX	87685	76	27 Apr
2016	MN	Waseca	H	SB	No	No	F Chisel/ FC	P0157AMX	87685	76	6 May
2016	MO	Bradford	L	SB	No	No	SP Disk/ FC	P1197AM	86450	76	16 Apr
2016	MO	Loess	H	SB	No	No	SP FC	P1197AM	83980	76	6 Apr
2016	MO	Troth3	H	SB	No	Yes	SP Disk/ FC	P1197AM	86450	76	13 Apr
2016	ND	Amenia3	H	SB	No	No	F Chisel/ FC	P9188AMX	93860	56	6 May
2016	ND	Durbin3	L	SB	Yes	No	F Chisel/ FC	P9188AMX	88920	56	6 May
2016	NE	Kyes	L	SB	No	Yes	No-till	P1197AMT	79040	76	5 May
2016	NE	SCAL3	H	Corn	No	Yes	No-till	P1197AMT	83980	76	12 May
2016	WI	Lorenzo	L	SB	No	No	No-till	P0157AMX	86450	76	23 Apr
2016	WI	Plano	H	SB	No	No	No-till	P0157AMX	86450	76	23 Apr

†L, Low; H, High; *FC, field cultivated; F, fall; Chis, Chisel; SP, spring.

Table 3.2. Sixteen different N fertilizer rates split over two times were replicated four times at each site. Treatments 1, 2, and 9-14 were used to calculate the economical N fertilizer rate for each site location. Treatments 1, 2, and 6 were used for soil respiration analysis.

Trt #	Planting N	Topdress N	Total N
	——————kg ha^{-1}——————		
1	0	0	0
2	45	0	45
3	90	0	90
4	135	0	135
5	180	0	180
6	225	0	225
7	270	0	270
8	315	0	315
9	45	45	90
10	45	90	135
11	45	135	180
12	45	180	225
13	45	225	270
14	45	270	315
15	90	90	180
16	90	180	270

Table 3.3 United States Department of Agriculture's defined hydrologic soil groups (HG). The HG 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 an HG, the least transmissive layer is used.

Hydrologic group	Runoff	Water transmission	Soil texture	K_{SAT}	Depth to water table	Depth to impermeable layer
				cm hr^{-1}	----------------cm-------------------	
A	Low	Unrestricted	>90% sand and <10% clay	>14.5	>61	>51
B	Mod. Low	Unrestricted	10-20% clay and 50-90% sand	3.6-14.5	>61	>51
C	Mod. 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 3.4. The United States Department of Agriculture's drainage classifications. Seven classes of natural drainage have been defined and refer to the frequency and duration of wet periods similar to those in which the soil formed. It should be noted that human modifications to drainage or irrigation were not considered in these classifications unless they greatly influenced the morphology of the soil.

Drainage Class	USDA Description
Excessively drained	- Water removed rapidly - Internal free water is very rare or deep - Coarse-textured soils with very high KSAT
Somewhat excessively drained	- Water removed rapidly - Internal free water is rare or deep - Coarse-textured soils with high KSAT
Well drained	- Water removed readily but not rapidly - Internal free water is deep to very deep - Water is available to plants for most of the growing season (in humid areas) - Wetness does not prevent growth of roots for prolonged periods of time - Mainly free from redoximorphic features
Moderately well drained	- Water is removed from the soil somewhat slowly throughout different times of the year - Internal free water is moderately deep and transitory - Soils are wet within the rooting zone for only a short time during the growing season but long enough for mesophytic plants to be affected - Periodically receive high rainfall - Low KSAT within upper 1 m of soil - Periodically receives high rainfall
Somewhat poorly drained	- Water is removed slowly - Soil is wet at shallow depths for a significant amount of time during the growing season - Internal free water is hallow to moderately deep and transitory to permanent - Wetness restricts the growth of mesophytic plants - Usually have either low to very low KSAT, a high water table, continuous rainfall, or additional water seepage
Poorly drained	- Water is removed slowly - Soil is wet at shallow depths periodically or remains wet for much of the growing season - Internal free water is shallow or very shallow and common or persistent - Free water is found at or near the surface for long periods of time throughout the growing season - Mesophytic plants cannot be grown unless artificially drained

Very poorly drained	- The soil is not continuously wet below the plow layer - Shallow water table is a result of low or very low KSAT or continuous rainfall - Water is removed very slowly - Standing water for much of the growing season - Internal free water is very shallow and is persistent or permanent - Most mesophytic plants cannot be grown unless artificially drained - Soils are commonly level or depressed and frequently have standing water

Table 3.5. Soil, weather, and canopy reflectance variables and potential two-way interactions that were examined using linear regression for relating the economic optimal nitrogen rate (EONR) to soil, weather, and canopy reflectance variables as delineated by USDA-NRCS defined hydrologic soil groups and drainage classifications. Analyses were performed for both at-planting and side-dress N times. The at-planting analysis did not included the weather or canopy reflectance variables as this information would not be available at the time of planting. For soil variables, all were considered for both the 0 to 30- and 0 to 60-cm depths except soil respiration.

Weather/Soil/Canopy Reflectance	Variable[†]
Weather	SDI
	GDD
	PPT
	AWDR
Measured	Clay
	PAWC
	SOM
	TOC
	TC
	pH
	Soil Resp.
	Clay × PAWC
	Clay × SOM
	Clay × TOC
	Clay × TC
	Clay × pH
	Clay × Soil Resp.
	SOM × TOC
	SOM × TC
	SOM × pH
	SOM × Soil Resp.
	TOC × TC
	TOC × pH
	TOC × Soil Resp.
	pH × Soil Resp.
SSURGO	Clay
	PAWC
	SOM
Weather × SSURGO	SDI × Clay
	SDI × PAWC
	SDI × SOM
	GDD × Clay
	GDD × PAWC
	GDD × SOM
	PPT × Clay
	PPT × PAWC
	PPT × SOM

	AWDR × Clay
	AWDR × PAWC
	AWDR × SOM
Weather × Measured	SDI × Clay
	SDI × PAWC
	SDI × SOM
	SDI × TOC
	SDI × TC
	SDI × pH
	SDI × Soil Resp.
	GDD × Clay
	GDD × PAWC
	GDD × SOM
	GDD × TOC
	GDD × TC
	GDD × pH
	GDD × Soil Resp.
	PPT × Clay
	PPT × PAWC
	PPT × SOM
	PPT × TOC
	PPT × TC
	PPT × pH
	PPT × Soil Resp.
	AWDR × Clay
	AWDR × PAWC
	AWDR × SOM
	AWDR × TOC
	AWDR × TC
	AWDR × pH
	AWDR × Soil Resp.
Canopy Reflectance	NDVI
	NDRE
	ISR
	ISR_{RE}
	CI
	CI_{RE}

† SDI, Shannon Diversity Index; GDD, growing degree days; PPT, total precipitation from time of planting to time of sensing (mm); AWDR, abundant and well distributed rainfall; Clay, % clay; PAWC, plant available water content (cm/30 cm); SOM, % soil organic matter; TOC, total organic carbon; TC, total carbon; Soil Resp., soil respiration; NDVI, Normalized Difference Vegetative Index; NDRE, Normalized Difference Red-Edge; ISR, Inverse Simple Ratio; ISR_{RE}, Inverse Simple Ratio Red-Edge; CI, Chlorophyll Index; CI_{RE}, Chlorophyll Index Red-Edge.

Table 3.6. Using linear regression, significant ($p < 0.05$) soil and weather variables found related to the economic optimum nitrogen rate (EONR) as delineated by USDA-NRCS defined hydrologic soil groups (HG) and drainage class. All four defined HGs (A, B, C, and D) were utilized. However, for this analysis sites within HGs A and D were clustered together as soils within these groups are prone to N loss. While seven drainage classifications exist, for this analysis sites were either well- (WD) or poorly-drained (PD). Results shown are for both N times (at-planting and side-dress). Weather variables were calculated using data from the time of planting to the time of sensing (approximately development stage V9).

N-time	HG Delineation	Variable[†]	Model	r^2	*p-value*
At-planting	A & D	-	-	-	-
	B-WD	SOM$_{30}$	y = 251 – 44 x SOM$_{30}$	0.64	0.001
	B-PD	PAWC$_{30}$ × SOM$_{60}$	y = 83 + 340 x (PAWC$_{30}$ x SOM$_{60}$)	0.74	0.039
	C-WD	Clay$_{30}$ × SOM$_{30}$	y = -296 + 447 x (Clay$_{30}$ x SOM$_{30}$)	0.78	0.012
	C-PD	TC	y = 260 – 75 x TC	0.32	0.016
Side-dress	A & D	SDI	y = 265 + 645 x SDI	0.54	0.015
	B-WD	Soil Resp.	y = 193 – 0.6 x Soil Resp.	0.55	0.003
	B-PD	SDI × Clay$_{60}$	y = 11 + 929 x (SDI x Clay$_{60}$)	0.85	0.017
	C-WD	SDI × Clay$_{30}$	y = -191 + 1324 x (SDI x Clay$_{30}$)	0.70	0.023
	C-PD	SDI × SRGO_PAWC$_{60}$	y = -171 + 100 x (SDI x SRGO_PAWC$_{60}$)	0.48	0.003

[†] SDI, Shannon Diversity Index; Clay$_{30}$, % clay in the upper 30 cm of soil; Clay$_{60}$, % clay in the upper 60 cm of soil; SOM$_{60}$, soil organic matter in the upper 30 cm of soil; GDD, growing degree days; PAWC$_{30}$, plant available water content in the upper 60 cm of soil (cm/30 cm); SRGO_PAWC$_{60}$, SSURGO gathered plant available water content in the upper 60 cm of soil (cm/30 cm); TC, total carbon in the first 30 cm of soil; Soil Resp., soil respiration in the first 30 cm of soil as measured using the 4-day Cornell Soil Health Assessment test.

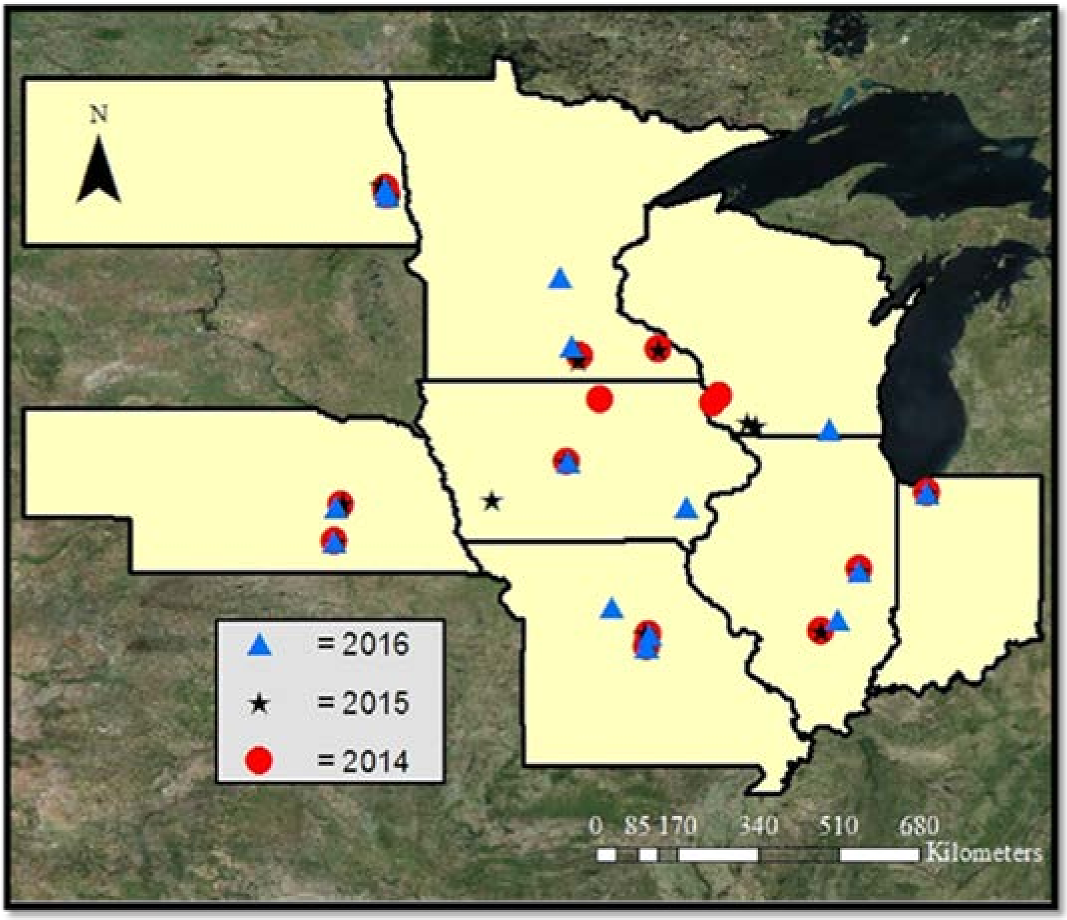

Figure 3.1. Field research sites were located within eight U.S. Midwest Corn Belt states (Iowa, Illinois, Indiana, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin). Each state contained two sites for each of the three growing seasons (2014 – 2016; Missouri had three sites for the 2016 growing season), totaling 49 sites.

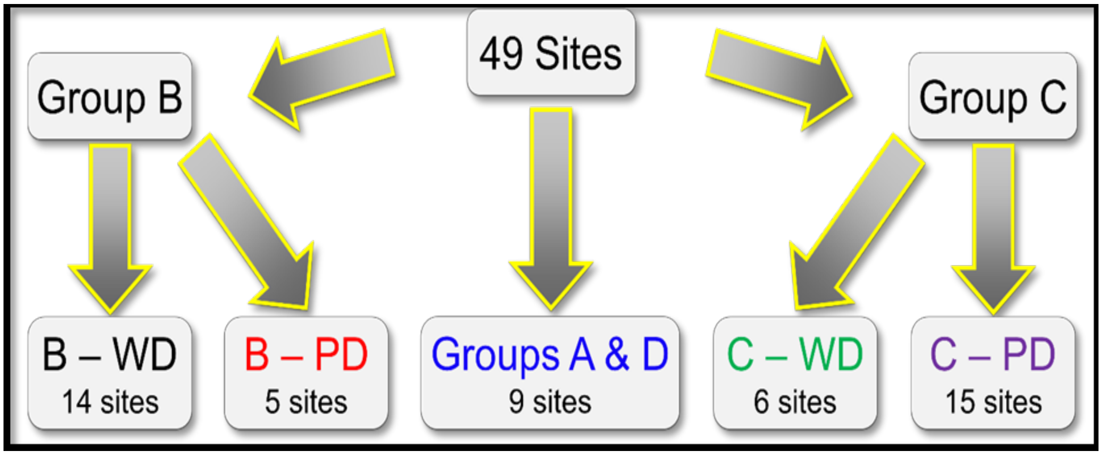

Figure 3.2. The delineation of all 49 site locations using United States Department of Agriculture – Natural Resource Conservation Service (USDA-NRCS) defined hydrologic soil group (HG) and drainage class. There are four total USDA-NRCS HG (A, B, C, D) with group A having the least potential for runoff and group D having the highest potential. Seven total USDA-NRCS drainage classifications have been defined, however for this analysis sites were considered either poorly-drained (PD) or well-drained (WD). Further information on HG or drainage class is found in text. Initial site delineation was made by using HG classification. Sites that fell within group A or D were combined. While these HG represent opposite soil water behavior in definition, sites within these groups are most prone to N loss via leaching or denitrification. Drainage class was then used for the final delineation of sites. A total of 5 separate groups resulted.

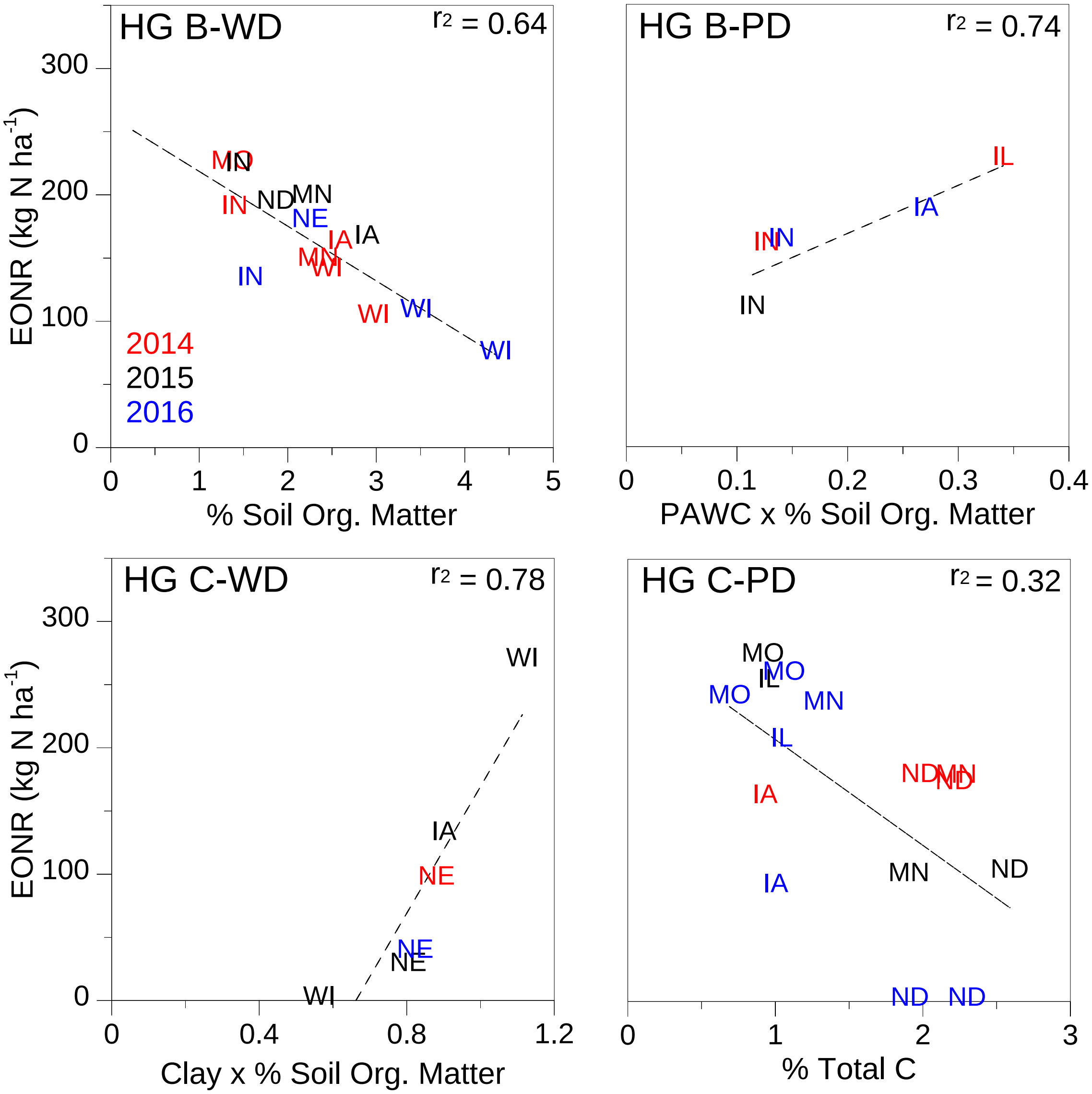

Figure 3.3. The most significant soil and/or weather variables related to the economic optimal N rates (EONR) for each delineated group for the at-planting N fertilizer timing. Each group was formed by using USDA-NRCS defined hydrologic soil groups (HG; A, B, C, and D) and drainage class information (WD = well-drained; PD = poorly-drained). Five total groups resulted (see Figure 3.2). There were no variables found significantly related to EONR for sites in HGs A and D (sites within HGs A and D were combined into one group). Therefore, only graphs for the remaining four groups are present. Percent soil organic matter (% Soil Org. Matter; 30 cm), the interaction between plant-available water content (PAWC; 60 cm) and % Soil Org. Matter, the interaction between clay (30 cm) and % Soil Org. Matter (30 cm), and total C (30 cm) were the variables most significantly related to EONR for HGs B-WD, B-PD, C-WD, and C-PD, respectively.

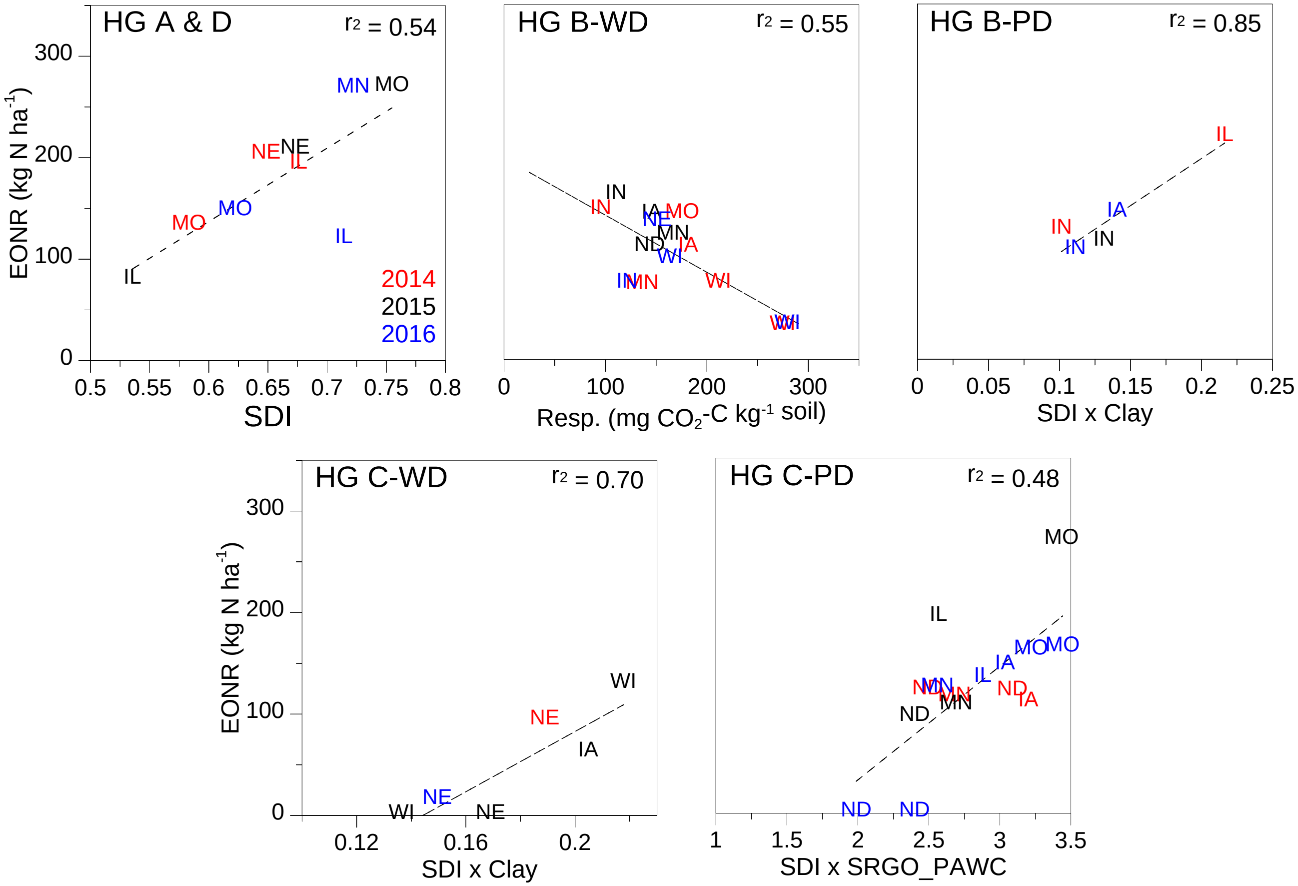

Figure 3.4. The most significant soil and/or weather variables related to the economic optimal N rates (EONR) for each delineated group for the side-dress N fertilizer timing. Each group was formed by using USDA-NRCS defined hydrologic soil groups (HG; A, B, C, and D) and drainage class information (WD = well-drained; PD = poorly-drained). Five total groups resulted (see Figure 3.2). The Shannon Diversity Index (SDI; evenness of rainfall from the time of planting to side-dress), soil respiration (Resp.; 30 cm), the interaction between SDI and clay (60 cm), the interaction between SDI and clay (30 cm), and the interaction between SDI and SSURGO plant-available water content (PAWC; 60 cm) were the variables most significantly related to EONR for HGs A and D, B-WD, B-PD, C-WD, and C-PD, respectively.

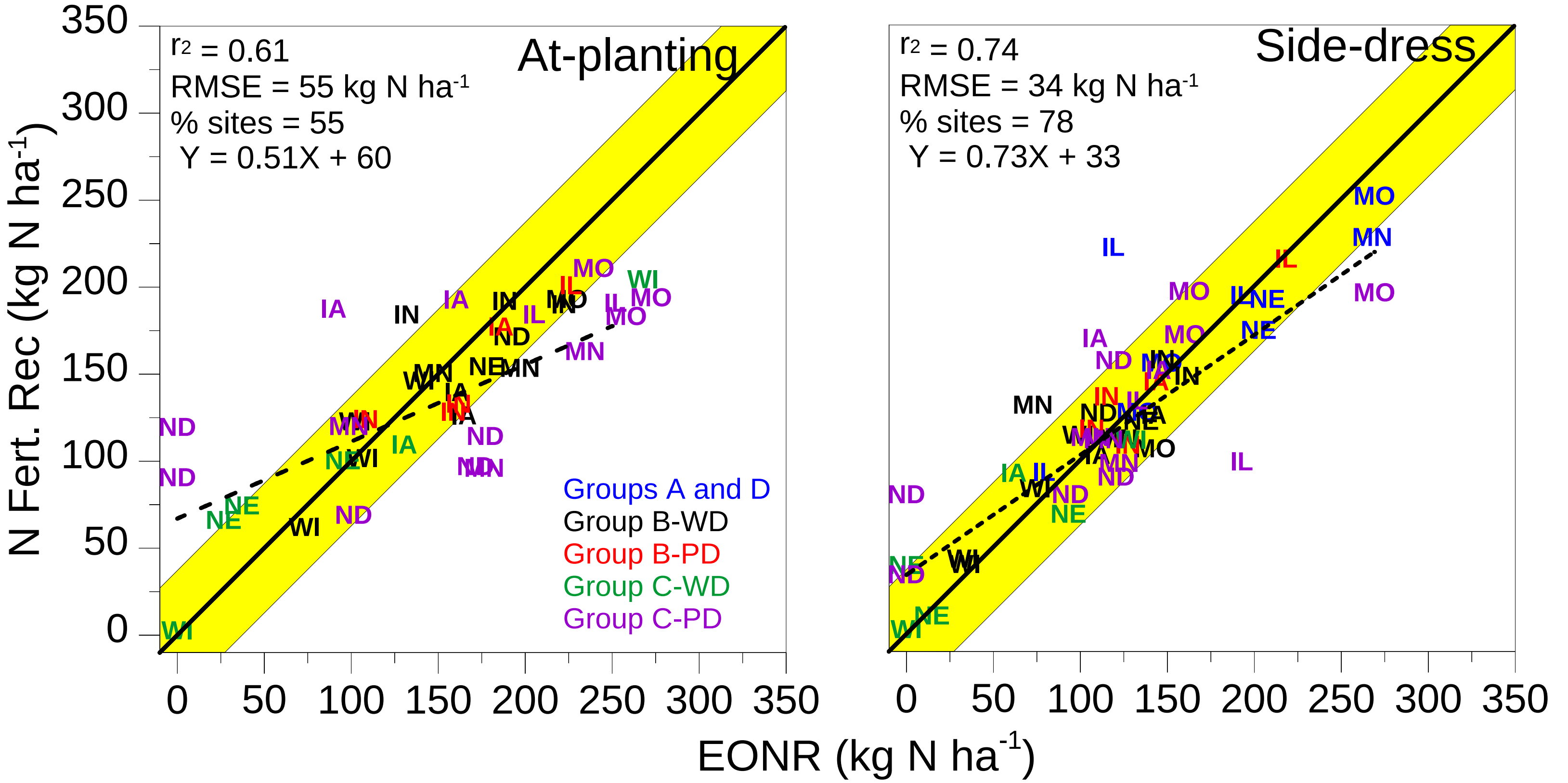

Figure 3.5. The economical optimum N fertilizer rate (EONR) compared to N recommendation models (N Fert. Rec) based on USDA-NRCS defined hydrologic soil groups (A, B, C, D) and drainage class (well-drained, WD; poorly-drained, PD) for both at-planting and side-dress N fertilizer timings. Overall, model N recommendations were better at side-dress. For the at-planting timing, no soil variable was found significantly related to EONR for soils in the A and D hydrologic soil groups. Therefore this approach is not applicable to those specific soils when N is applied all at-planting. Also, weather variables were not included in the at-planting models since seasonal weather is not available at the time of planting.

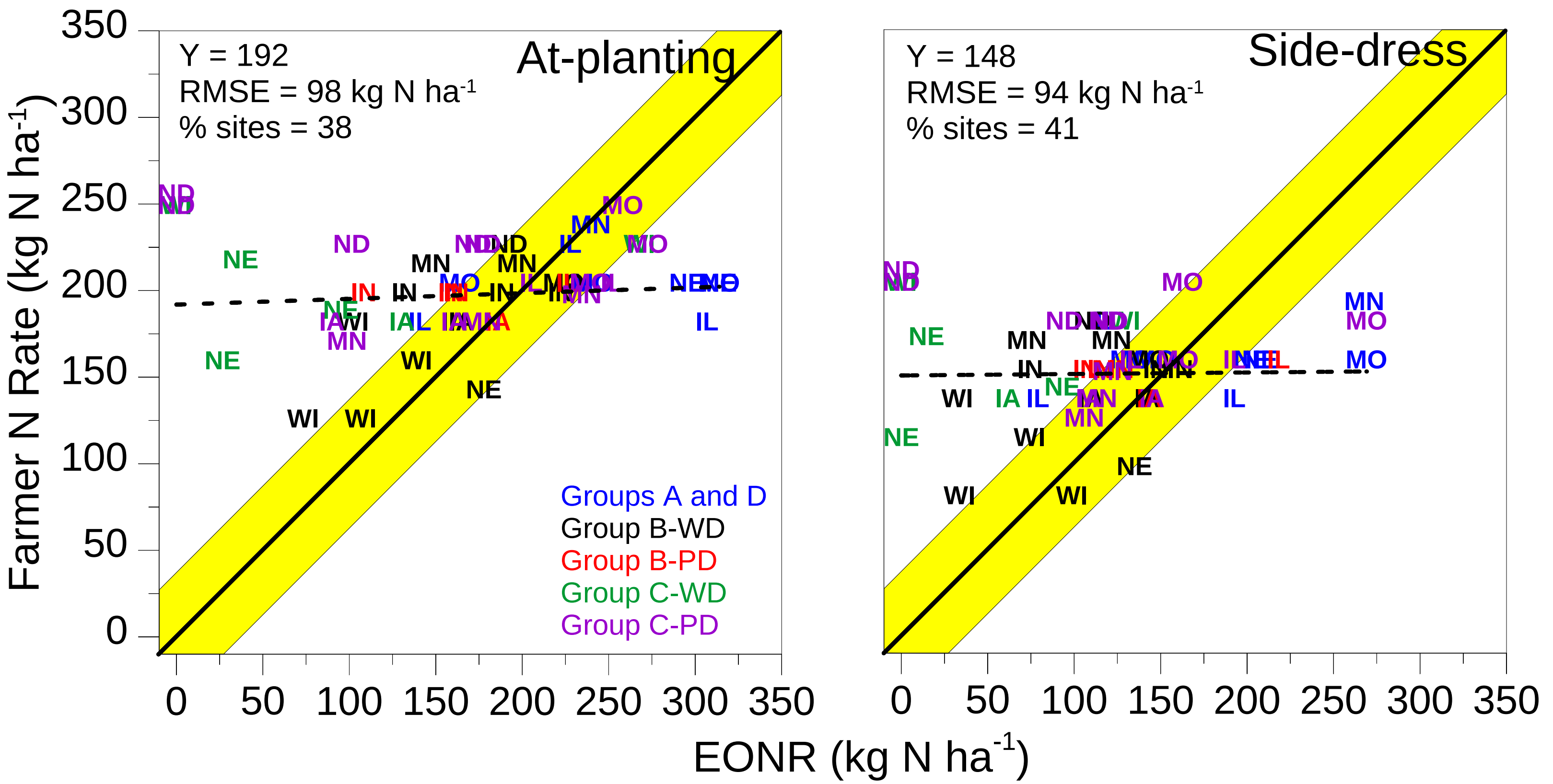

Figure 3.6. The economical optimum N fertilizer rate (EONR) compared to the Farmer's N recommendation (FNR). Overall, FNR were not significantly related to EONR (r^2 is not reported because of the lack of significance between EONR and FNR). However, when using the FNR 41 and 38 % of the sites were within 34 kg N ha^{-1} of EONR for the side-dress and at-planting N times, respectively.

Chapter 4: Validating N Fertilizer Recommendation Models Developed Using USDA-NRCS Hydrologic Soil Groups and Drainage Classifications

4.1 Abstract

Nitrogen fertilizer recommendations in corn (*Zea mays* L.) that match the economical optimum N fertilizer rate (EONR) are imperative to increasing profitability and preventing environmental contamination. However, processes influencing corn production (i.e. leaching and denitrification) are affected by soil and weather characteristics making it difficult to know when and how much N fertilizer to apply to match EONR. This analysis tests the performance of N recommendation models based on USDA-NRCS defined hydrologic soil groups (HG) and drainage classifications (Chapter 3 of this dissertation). A total of 182 site-years of corn N response trial data were gathered across six U.S. Midwest Corn Belt states to validate these models. Two analyses were performed, one for comparing the HG-based model recommendations to EONR and another comparing HG-based model recommendations with state-specific corn N rate tools. Appropriate measured and Soil Survey Geographic Database (SSURGO) soil variables along with weather information (gathered from the time of planting to the time of side-dress) were collected and used in conjunction with the applicable HG-based and state-specific N tools. Across all site-years and N timings the HG-based N recommendations were within 34 kg N ha^{-1} of EONR 38% of the time. State-specific N recommendation tools were within 34 kg N ha^{-1} of EONR 32% of the time. Following a two-tailed paired t-test these two approaches were not significantly

different from one another. When analyzed within each individual state, significant differences between approaches were observed. While showing some promise, these results suggest more research is required to determine the applicability of the HG-based model approach for corn N fertilizer management.

4.2 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 economical optimal N rate (EONR). These practices help maintain profit while minimizing N lost to the environment. Commonly, N fertilizer amount is over-applied to ensure maximum yield, resulting in poor N use efficiency and environmental pollution (Tremblay et al., 2012; Schröder et al., 2000; Shanahan et al., 2008). But because of the spatial and temporal variability of soil and weather factors impacting the fate of soil N, determining EONR before or early in the growing season is difficult. Corn N uptake is negligible early in the growing season, and when uncertain weather conditions prevail year-to-year, producers are motivated to split-apply N fertilizer mid-season to help synchronize application timing with crop uptake.

Historically, N fertilizer recommendations have been derived from expected grain yield (Blackmer et al., 1992; Gehl et al., 2005; Morris et al., 2018), but this fails to consider N need in response to specific interactive soil and weather conditions of the year ahead. Studies have established how soil and weather factors relate to corn N response (Xie et al., 2013, Tremblay et al., 2012). Understanding weather and soil variability, and their relationship to crop response measurements can be used to improve N fertilizer recommendations and help prevent environmental losses of N.

Spatial diversity of soil texture, soil organic matter (SOM), and plant available water (PAWC) across any given landscape combined with varying total rainfall, the evenness of rainfall, and temperature contribute to the complexities and fate of N in crops and the environment. Denitrification (the conversion of NO_3^- to $N0_x$ and N_2 gases) most often occurs in clayey textured soils experiencing anaerobic soil conditions from excessive rainfall and with 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 coarse textured soils (Power et al., 2001). Volatilization, (the loss of N through ammonia-NH_3 gas), 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. Research is needed to decide how these soil and weather variables can aid in making better N fertilizer recommendations.

Precipitation and temperature generally drive plant growth and influence soil conditions including soil microbial activity (Tremblay and Bélec, 2006), which ultimately influence corn yield. In years with above-average rainfall, corn has been generally found to respond more to applied 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, as well as by temperatures during July and August (Jeutong et al., 2000). The distribution or evenness of rainfall has also been found significant in describing corn yield responsiveness to N fertilizer, thus affecting yield (Shaw, 1964; Reeves et al., 1993; Tremblay et al., 2012). For example, frequent rainfall events in 51 studies were observed from 2006 to 2009 in several North American locations and were found to have large amounts of soil moisture early in the growing season that prompted N loss through denitrification and leaching, as well as increased the responsiveness to N fertilizer (Tremblay et al., 2012). Rainfall and temperature are widely accepted as variables directly impacting yield-limiting soil factors. These factors include oxygen levels, soil microbial activity, decomposition of organic matter (N mineralization), nutrient availability, plant-available water, and ultimately crop yield (Power et al., 2001; Tremblay, 2004; Tremblay and Bélec, 2006; Kyveryga et al., 2007; Shanahan et al., 2008; Tremblay et al., 2012).

Soil texture affects soil water flow, available N, plant-available water content (PAWC), the transportation and availability of ions (Schaetzl and Anderson, 2014), and crop yield (Zhu et al., 2009; Armstrong et al., 2009; Tremblay et al., 2012). While conflicting results exist, corn yield is generally greater on coarse-textured soils during wet years than during dry years. Also, corn yields tend to be greater on fine-textured soils during dry years than during wet years (Tremblay et al., 2011). Fifty-seven studies on smallholder farms in sub-Saharan Africa demonstrated the effect of soil texture on N fertilizer response. Nitrogen response was found to be greater on clay soils compared to loam or sandy soils (Chivenge et al., 2011). Similarly, in North America, finer textured soils were found to respond more to N fertilizer (Tremblay et al., 2012). Soil organic matter has also proven to be related to corn yield; soil organic matter makes up a small percentage of the total soil volume (<5%) but has a large effect on other soil properties (Sylvia et al., 2005). As SOM increases, soil aggregation improves, water infiltration rates rise and aeration increases. Collectively, these effects ultimately improve growing conditions.

Some of the above mentioned soil and weather interactions have been used by the USDA-NRCS to classify hydrologic soil groups (HG) and drainage classes. Each USDA-NRCS Soil Survey Geographical database (SSURGO) soil series is assigned a HG and drainage class (NRCS, 2007). 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 (NRCS, 2007). Soils that fall within the same HG are thought to respond similarly. 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 (Soil Survey Division Staff, 1993). When considering NO_3-N loss on a watershed scale, HG were found to be one of the most important factors in estimating NO_3-N movement and loss pathways (Blanchard and Lerch, 2000). In forested soils in southern Quebec, drainage class was significantly related to N transformation rates and internal N cycling (Ullah and Moore, 2009). On soils in North Carolina, and when analyzed by drainage class, the Illinois soil N test was found negatively related to EONR (Williams et al., 2007).

Most current publically available N fertilizer recommendation tools such as those based on yield goal (Stanford, 1973; Brown et al., 2004; Shapiro et al., 2008), pre-plant and pre-sidedress soil NO_3^- tests (Bundy et al., 1999; Franzen, 2010; Sawyer and

Mallarino, 2017), Maximum Return to Nitrogen (MRTN; Sawyer et al., 2006; Morris et al., 2018), and canopy reflectance (Kitchen et al., 2010; Dellinger et al., 2008; Scharf and Lory, 2009; Barker and Sawyer. 2010) do not use guideline subgroups based on soil or weather characteristics in the formulation of an N fertilizer recommendation. As described previously, using such soil and weather groupings has proven effective in determining the fate of N. Additionally, crop growth models including Maize-N (http://hybridmaize.unl.edu/maizen.shtml) simulate soil and crop processes in an attempt to estimate EONR. Varying success has been observed with these models (Setiyono et al., 2011; Thompson et al., 2015; Ransom et al., 2018). A recent study comparing 31 unique N recommendation tools, including all those mentioned above, was conducted across 49 different site locations in the US Midwest Corn Belt over three growing seasons (2014 – 2016). When compared to EONR, all N fertilizer recommendation tools evaluated had correlation coefficients < 0.20 (Ransom et al., 2018).

In Chapter Three of this dissertation, an attempt to improve the ability to estimate EONR by using guideline soil groups (as described above) was made. All 49 site locations were grouped by HG and drainage classification. Using simple linear regression, soil and weather variables were compared to EONR for each site in their respective delineated group. The resulting regression model equations from the most significant soil and weather variables within each delineated group were then used to estimate EONR for all site locations. This approach is commonly referred to as an empirical or statistical model (Tonitto et al., 2018). Outcomes using this empirical model were promising and outperformed the farmer N recommendation, but this test was applied back to the same dataset from which it was developed. A total of 55 and 78% of the sites were within 34 kg N ha^{-1} of EONR for the at-planting and side-dress N application times, respectively.

In general, empirically-based models are simple and are almost always easier to use than more complex process-based simulation models (such as Maize-N). Empirical models estimate environmental responses based on previous observations between a specific process and one or more controlled variables (Tonitto et al., 2018; Dalgaard et al., 2011; Leip et al., 2011; Waggoner, 1984). This approach does not model complete environmental systems and is specific to the region in which it was developed (Tonitto et al., 2018). Likewise, the models developed in Chapter Three of this dissertation are dependent on the observations used to derive the relationships between EONR and soil and weather information. Therefore, this approach's outcomes as presented in Chapter Three need to be validated.

Model validation is the process by which model estimates are compared to observed responses from datasets not originally used in the development of the proposed model (Hoffman and Hammonds, 1994; Aral, 2010). If validated, a model retains the accepted and consistent accuracy required for its intended application (Sargent, 1994; Curry et al., 1989). This process is thought to have a "yes" or "no" outcome. Namely, if a model is validated it fits the specified validation criteria. This criteria includes different statistical properties including goodness-of-fit (Aral, 2010), root-mean-square-error, or a range of allowable difference between the estimated and actual observations. However, a validated model does not always represent the best available model for that specific system (Rykiel, 1996; Aral, 2010). Nonetheless, for the models in Chapter Three to be determined relevant, validation is required.

The objective of this research was to validate the HG-based models developed in Chapter Three of this dissertation using independent data.

4.3 Materials and Methods

4.3.1 Site Information

Validation data were collected from six major land-grant universities [Iowa State University (Dr. J. Sawyer), Purdue University (Dr. J. Camberato), University of Missouri (Dr. N. Kitchen), North Dakota State University (Dr. D. Franzen), University of Nebraska (Dr. R. Ferguson), and the University of Wisconsin (Dr. C. Laboski] within the U.S. Corn Belt. The approach for this validation analysis was to gather data previously collected from N fertilizer application response studies conducted across a wide range of soil and weather conditions. Yield, soil, and weather measurements from these studies provided the information needed to generate N recommendations and N response functions. A total of 182 site-years of corn N response trials (75 at-planting and 107 side-dress site-years) were conducted from 1999 to 2018 in six Midwestern Corn Belt States (Figure 1). Many sites included multiple years from the same location. Brief descriptions of the collected datasets are presented in Tables 4.1 and 4.2.

4.3.2 Soil and Weather Measurements

Measured soil data necessary for model validation were gathered for all sites through original data collection. However, for sites with missing model specific soil data or not included in the original experiment, additional soil sampling was performed in the late summer and early fall of 2018. Sites requiring additional soil collection were sampled in a “Z” pattern across the footprint of the site via a Backsaver hand soil probe (JMC Soil Samplers, Newton, IA) with no less than 10 sampling points per site. Samples were taken and aggregated in 0-30 and 30-60 cm depth increments to satisfy the HG-based model requirements. Samples were sent to the University of Missouri Soil health Assessment Center and USDA-ARS Soil Quality Lab (located on the University of Missouri-Columbia campus) for further analyses. Analyses included the following: particle size determination through the pipette method, total carbon, total organic carbon, total inorganic carbon, soil organic matter (SOM), and soil respiration (R. Burt and Soil Survey Staff, 2014). Amount of clay (i.e., % clay) was calculated by using the particle size determination (R. Burt and Soil Survey Staff, 2014; Nelson and Sommers, 1996). Soil respiration was measured using the Cornell Soil Health Assessment (CASH) soil respiration test (Moebius-Clune et al., 2016; Zibilske, 1994). Plant Available Water Content was determined using the Saxton and Rawls formula (Saxton and Rawls, 2006). This equation uses measured sand and clay textural information along with SOM to determine soil moisture at both the permanent wilting point and field capacity. The difference between the soil moisture at field capacity and permanent wilting point produces PAWC.

The SSURGO data for each site was obtained from the USDA-NRCS via the "Web Soil Survey" website and the "Soil Data Viewer" plug-in available in ArcMap (ESRI, Redlands, CA) or the Soil Web (University of California, Davis, CA). If more than one SSURGO mapping unit was assigned to the research site, the most dominant mapping unit was chosen. Data collected from SSURGO included PAWC, HG, and drainage classification.

Each site's weather data were collected either using 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. Daily precipitation and any irrigation was used to calculate the Shannon Diversity Index (a measure of evenness; SDI; Tremblay et al., 2012) from the time of planting to the time of side-dress. This variable was calculated as:

$$SDI = \left[-\sum pi \frac{ln(pi)}{ln(n)}\right] \qquad [1]$$

where pi = daily rainfall/total precipitation and n = number of days in the specified time being used. Irrigation amounts were not recorded for the 2017 NE locations and therefore were not included in the total precipitation amounts.

4.3.3 Site Delineation by Hydrologic Soil Group and Drainage Class

Hydrologic soil group and drainage classification was gathered from the SSURGO database via Soil Web (University of California, Davis, CA). Initial site delineation was made by using HG and drainage classification. Further information on site delineation is found in chapter three of this dissertation and Figure 4.2 as well as Tables 4.3 and 4.4 in this chapter.

4.3.4 Evaluation and Statistics

Data were analyzed on a site-level basis by delineated HG using SAS version 9.2 (SAS Institute Inc., Cary, NC). First, EONR values were calculated for both the at-planting and split-N treatments. Some of the outside datasets already had EONR values calculated for each respective N fertilizer timing (all used a 10:1 corn: N price ratio) while others did not. A corn grain price of \$ 0.158 kg^{-1} (\$4.00 bu^{-1}) and N fertilizer cost, \$0.88 kg N^{-1} (\$0.40 lb^{-1}) was used for datasets needing EONR calculated. The EONR calculation was as follows:

$$EONR = \frac{-b-(N{:}corn\ price)}{(2c)} \qquad [2]$$

where b and c = linear and quadratic response coefficients from optimized quadratic function. For evaluating HG N recommendation models for corn that received N fertilizer 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 N fertilizer timings.

The performance of each developed model was evaluated in the following ways:

1. Using absolute differences, two-tailed t-tests between HG-based model (model$_{\mathrm{DIFF}}$) and state-specific (state$_{\mathrm{DIFF}}$) recommendations and EONR were used to determine if the HG-based and state-specific approaches were

statistically different (α = 0.10). All state-specific approaches are listed in Table 4.5.

2. The percentage of sites within 34 kg N ha^{-1} of EONR. A large percentage of sites within 34 kg N ha^{-1} of EONR leads to better model and/or approach performance.
3. The root mean square error (RMSE), which was calculated as follows:

$$RMSE = \sqrt{\frac{\sum(N_{Mod}-N_{EONR})^2}{n}} \qquad [3]$$

where N_{Mod} = the model N rate recommendation, N_{EONR} is the measured EONR, and n = the total number of site years. Smaller RMSE values propose better performance.

4. Using linear regression, the comparison between the HG-based model and state-specific N recommendations to the site level EONR. If no relationship was observed (α = 0.10) the respective slope was considered zero and only the intercept is shown. Comparisons with no significant relationship to EONR suggest a lack of sensitivity to site-specific corn N need.
5. Using a t- (n<25) or z-test (n>25) for parallelism, the slopes between the HG-based model and state-specific N recommendations were compared (α = 0.10). Tests were performed when data was aggregated by approach and by state across all site-years. These tests allowed for the N response relationships to be compared between HG-based and state-specific approaches. In addition, this process was used to test HG-based model

performance differences between N application timings (at-planting v. side-dress) across all site-years.

4.4 Results and Discussion

4.4.1 Site Delineation

Site delineation resulted in five groups (Figure 4.2). A total of 50 sites were in HGs A and D, 37 sites in HG B-WD, 31 sites in HG B-PD, 13 sites in HG C-WD, and 50 sites in HG C-PD. Figures 4.3 to 4.5 graphically show the comparison between model-estimated N recommendations and the end-of-season calculated EONR with Figures 4.6 to 4.12 showing the comparison between HG-based and state-specific N recommendations. Sites within the yellow band are those within 34 kg N ha^{-1} of EONR and represent satisfactory model performance. Sites above and below the yellow band are those in which the model over- or under-estimated EONR.

4.4.2 Overall Performance

For the at-planting HG-based models, 37% of the recommendations were within 34 kg N ha^{-1} of EONR with an RMSE of 70 kg N ha^{-1} with the overall model being related to EONR ($p = 0.003$). Comparatively, a total of 42% of the N fertilizer recommendations were within 34 kg N ha^{-1} of EONR with an RMSE of 68 kg N ha^{-1} for the side-dress HG-based recommendations. This model was also found related to EONR ($p < 0.001$). However, when relating the N response relationships between these two N application times a significant difference was observed ($p < 0.001$). Therefore, the side-dress HG-based model was more sensitive to corn N need. Performance differences between N application times are due to the susceptibility for N loss early in the growing season. While contrasting observations exist, when applied before the period of rapid N uptake (V5 – V9; Abendroth et al., 2011) the fate of N is more uncertain then when applied in-season (Randall and Vetsch, 2005; Bakhsh et al., 2006). Therefore, estimating corn N need at the time of planting is likely to be less accurate than when estimated in-season. Split applying N allows synchronization between application and rapid N uptake (IPNI, 2018). Additionally, weather information from the time of planting to the time of side-dress can be included in the side-dress HG-based model accounting, at least partially, for temporal variability. This leads to more accurate estimations of corn N need and ultimately more model recommendations within 34 kg N ha^{-1} of EONR.

4.4.3 Model Performance for N Applied At-planting

4.4.3.1 HGs A and D

A total of 16 sites fell within HGs A and D for the at-planting N time. However, chapter three of this dissertation revealed there were no soil variables used in the development of these models significantly related to EONR for this N application time. This was not surprising as the only soil or weather variable found related to EONR for these soils for the side-dress analysis was SDI, a variable not included in the at-planting analysis. Therefore, for these soils when applying all N fertilizer at-planting another recommendation method would be needed.

4.4.3.2 HG B-WD

Soil organic matter in the first 30 cm of soil was used to estimate EONR for HG B-WD. Using this model resulted in 46% of the sites being within 34 kg N ha^{-1} of EONR with an RMSE of 47 kg N ha^{-1} (HG B-WD graph in Figure 4.4). This model was not significantly related to EONR (p = 0.11). However, 16 of the 22 at-planting site-years found in this HG came from one field in central Iowa (IA). Nitrogen response data on this site were collected from 2000 to 2016. In addition, SOM information needed to validate the model was not available for these years. Therefore, this site was soil sampled in the fall of 2018 to determine SOM content, assumed to be relatively stable over this time period. Essentially, 2018 SOM content was used in proxy of the year-specific SOM to estimate EONR. This resulted in the same N recommendation for all years. Interestingly, over the first half of the N response experiment at this site (first eight years) EONR averaged 113 kg N ha^{-1}. The remaining nine years had an average EONR of 152 kg N ha^{-1}. This was likely due to site management. This site was conventionally tilled in the fall (chisel plow) and spring (disk and field cultivator) every year. Others have found a decline in SOM content with continuous forms of conventional tillage (Linn and Doran, 1984; Sylvia et al., 2005; Zuber et al., 2015). Conventional tillage increases soil temperature and oxygen levels, breaks up otherwise protected organic residues, which makes C more accessible stimulating microbial activity ultimately consuming more soil organic matter (Balesdent et al., 1988; Weil and Brady, 2017). Additionally, tillage makes soil more susceptible to erosion leading to greater SOM loss (Kern and Johnson, 1993; Balesdent et al., 2000; Laird and Chang, 2013). Generally, declining levels of SOM results in less N mineralization and a greater need for added N fertilizer (McCarty et al., 1995).

Iowa State University Extension guidelines suggest agricultural soils should be sampled every 2 – 4 years (Sawyer et al., 2003). Whether or not SOM changed significantly over this 16 year period is unknown. Perhaps the model performance for this delineated group would have been more sensitive to crop N need if year-specific SOM amounts were available for this site.

4.4.3.3 HGs B-PD and C-WD

Similar soil interactions were used to estimate EONR for HG B-PD and HG C-WD (HG B-PD and HG C-WD graphs in Figure 4.4). For HG B-PD the interaction between PAWC and SOM (in the top 60 cm of soil) was used to estimate EONR. Using the HG-PD model resulted in 56% of the sites being within 34 kg N ha^{-1} of EONR with an RMSE of 61 kg N ha^{-1}. This model was not related to EONR ($p = 0.31$). Five of the seven IN site-years within this group were located at the Pinney Purdue Agricultural Center (PPAC) and were within 600-m of one another (D-South, A4, and C4). Using this model resulted in similar N fertilizer recommendations across these site-years except for the 2013 D-South location. The D-South site had nearly three times the amount of SOM (approximately 10% SOM) and twice the PAWC as the other sites resulting in a model N recommendation that over-estimated EONR and was approximately 100 kg N ha^{-1} greater than the other site-years. Poor model performance for this site may be due to the range in SOM levels originally used to develop it. The five sites originally used to create the linear-based HG B-PD model (see chapter three) had SOM levels ranging from 2.1 to 4.2%. Therefore, the D-South SOM value was more than twice the upper limit from which the model was developed, and potentially the reason the model over-estimated the N recommendation. Model performance may have improved if sites with a wider range in SOM values were included in the creation of this model.

The interaction between clay and SOM (in the top 30 cm of soil) was used to estimate EONR for HG C-WD. Only three sites fell within this group for the at-planting N time, thus the validation for this specific situation is weak. All three sites were located in ND. The model recommendation for two of the sites was within 34 kg N ha^{-1} of EONR while the other recommendation under-estimated EONR by approximately 75 kg N ha^{-1}. Additionally, this model was found positively related to EONR (p = 0.02). Ultimately, many more sites are required to validate this particular model.

4.4.3.4 HG C-PD

The amount of total C (in the top 30 cm of soil) was used to estimate EONR for HG C-PD. Only 26% of the site-years in this group were within 34 kg N ha^{-1} of EONR with an RMSE of 89 kg N ha^{-1} (HG C-PD graph in Figure 4.8). This model was not related to EONR (p = 0.16). Recommendations for 13 of the 16 IA site-years under-estimated EONR. Most of these site-years were located at the South and Southeast IA locations. The Southeast location is assigned to HG C. However, the soil textural analysis revealed a site average clay content of 37.4%. Therefore, these site-years may respond more similarly to soils within HG D. Because the HG-based approach does not have the appropriate N recommendation model for HG A or D soils another N fertilizer recommendation approach would have to be utilized altogether for these site-years.

4.4.4 Model Performance for Side-dress N Applications

4.4.4.1 HGs A and D

The SDI was used to estimate EONR for soils within HGs A and D. A total of 49% of the model recommendations were within 34 kg N ha^{-1} of EONR with an RMSE of 65 kg N ha^{-1} (HGs A and D graph in Figure 4.5). This model was positively related to EONR (p = 0.001). The relationship between SDI and EONR (as described in chapter three) was based on weather information from the time of planting to side-dress. This period is roughly one-third of the total growing season allowing for weather, and in particular rainfall, to impact that portion of the growing season when the crop N uptake is minimal. Impact is season-long affecting the fate of N, but vulnerability for N loss is greatest during the spring or fall (Randall and Vetsch, 2005). The positive relationship between SDI and EONR was encouraging, supporting the concept others have made that N fertilizer need increases with precipitation evenness (Tremblay et al., 2012). Site-years where model-predicted N rate over-estimated EONR had high SDI values from the time of planting to the time of side-dress, but low SDI values following side-dress (data not included). This produced inaccurate model recommendations. This was evident for the 2014 and 2015 IA Northwest site-years. These site-years had SDI values of 0.66 and 0.67 before side-dress and SDI values of 0.57 and 0.58 following side-dress. Inversely, site-years where the model-predicted N rate under-estimated EONR had low SDI values from the time of planting to the time of side-dress, but high SDI values following side-dress. This was true for the 2012 and 2014 IA, Northwest site-years. These site-years had SDI values of 0.53 and 0.42 prior to side-dress and SDI values of 0.59 and 0.52 following side-dress. These results demonstrate how precipitation patterns following side-dress affect crop N need, and the difficulty in estimating season long N fertilizer need with weather from only a portion of the season.

4.4.4.2 HG B-WD

Soil respiration was used to estimate EONR for HG B-WD (HG B-WD graph in Figure 4.5). Thirty-nine percent of the site-year N recommendations in this group were within 34 kg N ha^{-1} of EONR with a RMSE of 55 kg N ha^{-1}. This model was not related to EONR (p = 0.19). The Cornell Soil Health Assessment test uses capillary forces and a known volume of water (7.5 ml) to re-wet the 20 g dried soil sample. This method has been found to inaccurately measure mineralizable carbon on coarse-textured soils (Franzluebbers and Haney, 2017). The USDA-NRCS classified the two 2016 NE site-years as HG B containing 65% sand. However, actual analysis from these sites were found to contain ~90% sand. This partially qualifies them to be in HG A (soils that are excessively drained). Interestingly, when using the HGs A and D SDI-based N recommendation model for these NE site-years, performance improved. The difference between model recommendations and EONR decreased by over 20 kg N ha^{-1}. Additionally, four of the six IN site-years included in this group were from the same field located at the Southwest Purdue Agricultural Center (SWPAC). Soil samples taken in the fall of 2018 were used to estimate soil respiration for 2006, 2008, 2011, and 2012 growing seasons. This is problematic since soil respiration is sensitive to temporal variability (Linn and Doran, 1984; Howard and Howard, 1993; Davidson and Janssens, 2006). Model performance may have improved if year-specific soil was used for soil respiration analyses.

4.4.4.3 HG B-PD and C-WD

The interaction between clay and SDI was used to estimate EONR for HG B-PD (SDI × clay in the top 60 cm; HG B-PD graph in Figure 4.6). All 21 site-years included in this group were from two research farms in IN. Five site-years were located at the Agronomy Center for Research and Education (ACRE) and the remaining site-years at the PPAC. A total of 11 site-years (52%) were within 34 kg N ha^{-1} of EONR with an RMSE of 46 kg N ha^{-1}. This model was not related to EONR ($p = 0.20$). For eight of the 10 site-years not within 34 kg N ha^{-1} of EONR, the HG B-PD model under-estimated EONR. Rainfall evenness, as measured by SDI, partially drives this model and was calculated using weather data from the time of planting to the time of side-dress. The site-years in which the model N recommendation under-estimated EONR experienced post side-dress weather that increased N loss and therefore required a greater amount of fertilizer N to reach EONR. This is evident in the 2012 PPAC and 2015 ACRE site-years. Before side-dress these sites experienced SDI values of 0.27 and 0.45 while following side-dress SDI values increased to 0.60 and 0.66 for the PPAC and ACRE site-years, respectively. As determined in chapter three, increasing SDI values suggest anaerobic conditions and suppressed N mineralization and/or N loss through leaching and denitrification loss pathways.

The interaction between clay and SDI was also used to estimate EONR for HG C-WD (SDI × clay in the top 30 cm; HG C-WD graph in Figure 4.5). These sites produced some of the best validation results of this study. Here there were 10 site-years included in this group. One site from IN, three from MO, and six from NE. Seven of these site-years (70%) were within 34 kg N ha^{-1} of EONR; and the overall RMSE was only 39 kg N ha^{-1}. This model was positively related to EONR (p = 0.003). The HG C-WD model over-estimated EONR for three site-years (all from NE), but only one site over-estimated N need by more than 50 kg N ha^{-1}. These three site-years were all included in the 2017 growing season and were irrigated. Unfortunately, irrigation timing and amounts were not recorded during the 2017 growing season.

4.4.4.4 HG C-PD

For HG C-PD, the interaction between SDI and SSURGO-PAWC (in the top 60 cm of soil) was used to estimate EONR (HG C-PD graph in Figure 4.5). A total of 27 site-years, all located in either IA or IN, were included in this group with only 4 site-years (15%) being within 34 kg N ha^{-1} of EONR, and with one of the highest RMSE of this investigation (96 kg N ha^{-1}). However, this model was positively related to EONR (p = 0.10). Seventeen (63%) of the HG C-PD model recommendations not within 34 kg N ha^{-1} of EONR under-estimated N need. It should be noted at these site locations SSURGO PAWC was nearly identical to the PAWC estimated using the Saxton and Rawls equation (Saxton and Rawls, 2006), ruling out inaccurate SSURGO PAWC values as a cause for poor model performance. Similar to other models already mentioned the HG C-PD model utilizes weather from the time of planting to the time of side-dress to estimate SDI. When SDI values increase following side-dressing applications, N loss is likely and the amount of N fertilizer needed to reach EONR increases. Ultimately this results in an under-estimation of EONR. This situation was evident in several site-years at both the IA and IN locations. Contrastingly, during some growing seasons at the IA locations, SDI values were greater before side-dress than they were following side-dress, leading to an over-estimation of EONR.

4.4.5 Model Performance Compared to State-Specific N Recommendations

4.4.5.1 Overall Performance between Approaches

Across all site-years, the HG-based model and state-specific recommendations performed similarly. Thirty eight percent of the HG-based N recommendations were within 34 kg N ha^{-1} of EONR with an RMSE of 70 kg N ha^{-1} (Model graph in Figure 4.6). The HG-based approach was related to EONR ($p < 0.001$). Comparatively, 32% of the state-specific N recommendations were within 34 kg N ha^{-1} of EONR with an RMSE of 80 kg N ha^{-1} (State-Specific graph in Figure 4.6). The state-specific approach was also related to EONR, but weakly ($p = 0.07$). On average, recommendations from these two methods were the same. However, a difference between the N responses of the HG-based and state-specific approaches was observed ($p < 0.001$). This suggests the HG-based model was more sensitive to corn N need. Also, when analyzed by individual state, significant differences were observed between $\text{model}_{\text{DIFF}}$ and $\text{state}_{\text{DIFF}}$ and are discussed below.

4.4.5.2 States Using Maximum Return to Nitrogen Recommendations

Four of the six states included in this validation dataset employ the MRTN approach to corn N management (IA, IN, ND, and WI). Each participating state uses within-state empirical N response trial data coupled with an economic analysis to determine the N rate at which yield is maximized (i.e. MRTN; Morris et al., 2018). The number of N response trials used within each state to determine the MRTN is variable. As of 2016, a total of 371, 150, and 138 N response trials were used for MRTN development in IA, IN, and WI, respectively (Morris et al., 2018). It should be noted that year-specific MRTN rates were not available therefore the calculated 2018 MRTN rates were employed.

The performance of the MRTN tool was variable across this validation dataset. For the IA site-years, HG-based N fertilizer recommendations for 11 of 68 site-years (16%) were within 34 kg N ha^{-1} of EONR with an RMSE of 86 kg N ha^{-1} (Model graph in Figure 4.7). This approach was not related to EONR ($p = 0.54$). When using the IA-specific MRTN 23 of 68 site-years (34%) were within 34 kg N ha^{-1} of EONR with an RMSE of 58 kg N ha^{-1} (State-Specific graph in Figure 4.7). Similar to the HG-based model, this approach was not related to EONR ($p = 0.87$). Additionally, N responses were the same ($p = 0.55$). However, recommendations from these two methods were statistically found to be unique. The performance of the HG-based model may have improved, especially for the Southeast site-years, if year-specific soil samples were available for model inclusion. However, the IA-specific MRTN is user friendly, fast to use, and does not require soil sampling, perhaps making it a more appealing and adoptable option for N fertilizer management in IA.

The MRTN tool was less accurate in IN, WI, and ND. For the IN site-years, using the HG-based model resulted in a total of 29 of 67 site-years (43%) being within 34 kg N ha^{-1} of EONR with an RMSE of 68 kg N ha^{-1} (Model graph in Figure 4.8). This approach was related to EONR ($p < 0.001$). Using the MRTN tool unique to IN resulted in 22 site-years (33%) being within 34 kg N ha^{-1} of EONR with an RMSE of 73 kg N ha^{-1} (State-Specific graph in Figure 4.8). This approach was also related to EONR (p = 0.02). For the WI site-years, 6 of 13 site-years (46%) had HG-based model recommendations within 34 kg N ha^{-1} of EONR, with an RMSE of 53 kg N ha^{-1} and was weakly related to EONR (p = 0.07; Model graph in Figure 4.9). When using the MRTN tool unique to WI only three of 13 sites (23%) were within 34 kg N ha^{-1} of EONR, with an RMSE of 78 kg N ha^{-1} and was not related to EONR (p = 0.38); State-Specific graph in Figure 4.9). This suggests the WI MRTN had poor sensitivity to corn N need. For ND, the HG-based model N recommendations were especially promising. Sites were within 34 kg N ha^{-1} of EONR 78% of the time with an RMSE of 39 kg N ha^{-1} (Model Graph in Figure 4.10). This approach was related to EONR (p = 0.01). There were no ND-specific MRTN N recommendations within 34 kg N ha^{-1} of EONR, and the RMSE was 95 kg N ha^{-1} (State-Specific graph in Figure 4.10). Also, no relationship to EONR was observed (p = 0.52). Following a two-tailed paired t-test between $model_{DIFF}$ and $state_{DIFF}$ for IN, WI, and ND revealed there was only a significant difference between the HG-based model and ND state-specific recommendations. However, an N response comparison between the HG-based and state-specific approaches revealed differences in every case (IN, WI, and ND). Therefore, the HG-based model is more adaptable to site-specific N need. It should be noted that one of the inputs for the ND-specific MRTN calculation is pre-season soil nitrate concentration (down to 60 cm), but this was not available for inclusion. Accounting for this allows the MRTN recommendation to reduce to match site-specific needs. Since the majority of the sites gave over-estimated N recommendations, soil nitrate information would have improved this state recommendation.

4.4.5.3 States Using Yield Goal recommendations

Using different yield goal derivations for calculating N fertilizer recommendations (Table 4.5), MO and NE sites were also compared to HG model recommendations. For these states unique approaches exist using expected yield, internal N requirement, subtractions or additions to the base N rate, and credits or debits from the previous crop to formulate an N fertilizer recommendation (Morris et al., 2018). Both the MO and NE yield goal recommendation tools performed similarly.

For the limited sites from MO, all HG-based model recommendations were within 34 kg N ha^{-1} of EONR with an RMSE of 11 kg N ha^{-1} (Model graph in Figure 4.11). This approach was related to EONR ($p < 0.001$). When using the MO state-specific N recommendation tool zero recommendations were within 34 kg N ha^{-1} of EONR (State-Specific graph in Figure 4.11). Recommendations from these two methods were unique. In addition, no relationship was observed between EONR and the MO state-specific tool (p-value = 0.22). While a statistical significance between the HG-based model and MO yield goal was found using this analysis, only five site-years were included. Therefore, more data is needed to compare the relationships between these two N recommendation approaches and EONR.

For NE, seven of 14 HG-based model recommendations (50%) were within 34 kg N ha^{-1} of EONR with a RMSE 53kg N ha^{-1} (Model graph in Figure 4.12). When using the

NE state yield goal calculation four of 14 N recommendations (29%) were within 34 kg N ha^{-1} of EONR with an RMSE of 80 kg N ha^{-1} (State-Specific graph in Figure 4.12 Recommendations from these two methods were statistically found to be unique. Also, no relationship was observed between EONR and the NE yield goal. Similar to the MO state-specific tool, this suggests that the NE state-specific tool does not account for site-specific N need. The NE yield goal calculation requires several inputs, two of which are irrigation amount and irrigation water nitrate concentration. Irrigation amounts were not recorded for 2017 and irrigation water nitrate concentrations not offered for either year. If this information was available the NE yield goal performance may have improved.

4.5 Conclusions

Predicting corn N need is difficult due to spatial and temporal variability. However, increasing the accuracy of N fertilizer recommendations is imperative for sustainable corn N management. Several tools have been developed for this purpose, but with varying success. Here a proposed tool was evaluated based on identifying a site relative to HG, and using HG-specific models that employed soil and/or precipitation information for making an N fertilizer recommendation. When model performance was compared by N timing, a greater percentage of sites were within 34 kg N ha^{-1} of EONR for sites with N applied as a side-dress (Figure 4.3; 42% as compared to 37%). Both the at-planting and side-dress models, across all site-years, were found related to EONR. However, following an N response comparison, the side-dress model was observed to be more sensitive to N need. Model performance may have been hindered for both N timings due to using soil data gathered in 2018 in-place of year-specific data. When separated by N timing and HG-based delineation groups, a wide range in performance was observed.

When evaluating the HG-based and state-specific approaches across all site-years there was no significant difference between model$_{\mathrm{DIFF}}$ and state$_{\mathrm{DIFF}}$. However, uniqueness between approaches was observed following an N response comparison with the HG-based model being more adaptable to corn N need. Additionally, comparing model$_{\mathrm{DIFF}}$ and state$_{\mathrm{DIFF}}$ within each respective state revealed mixed performances. For example, significant differences between model$_{\mathrm{DIFF}}$ and state$_{\mathrm{DIFF}}$ for IA, ND, NE, and MO were observed with IA-specific MRTN outperforming the HG-based model and the HG-based model outperforming ND-specific MRTN and NE and MO yield goals. There was no significant difference found between model$_{\mathrm{DIFF}}$ and state$_{\mathrm{DIFF}}$ for IN and WI. Interestingly, within each respective state uniqueness among N responses were found with the HG-based approach outperforming the state-specific methods. These observations suggest while the HG-based and state-specific approaches may be similar on average, the HG-based model was more sensitive to the spatial and temporal variability found at each site.

The performance of current N recommendation tools is such that dependable estimates of corn N need across years and sites is unavailable (Morris et al., 2018). This is in large part due to the complexity of the N-cycle across and among fields. These tools, with the exception of process-based computer models (i.e., Adapt-N, Maize-N, Encirca, etc.), attempt to estimate corn N need without taking into account N processes dependent on soil properties and site-specific weather events. The empirical and HG-based models presented in this dissertation incorporate in a simplified way these soil and weather (water) interactions to better estimate N-cycle processes and ultimately EONR. For example, initial site grouping was determined based on soil and/or soil-water characteristics such as K_{SAT}, soil texture, depth to water table or restrictive layer, the likelihood of ponding, etc. This grouping combined soils where N cycle processes are likely to respond similarly given alike environmental conditions. Furthermore, within each group specific soil and weather variables determined to be most related to EONR were used to estimate corn N need. This approach allowed for a more accurate prediction of the fate of N as compared to MRTN and yield goal state-specific approaches.

However, it should be noted that the dataset used to create these HG-based models did not contain site-years that experienced severely wet or dry conditions. Being an empirically based model the HG approach is limited to the environments in which it was based. Therefore, the lack of extreme weather conditions restricts the use of this N recommendation approach. The varying results from this analysis and the lack of observations for some HG-based groups suggests that further research is required to better understand the applicability of the HG-based N fertilizer recommendation approach. Preferably, current or additional N response studies could be used to ensure all required data measurements are collected for both N fertilizer recommendation approaches.

4.6 Bibliography

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR 1009. Iowa State University Extension, Ames, IA.

Aral, M.M. 2010. Environmental modeling and health risk analysis (ACTS/RISK). Springer Science + Business Media B.V. 2010. doi:10.1007/978-90-481-8608-2_2

Armstrong R.D., J. Fitzpatrick, M.A. Rab, P.D. Fisher, M. Abuzar, P.D. Fisher, and G.J. O'Leary. 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 Pasture Sci. 60:870-884. doi:10.1071/CP08349

Bakhsh, A., R.S. Kanwar, C. Pederson, and T.B. Bailey. 2006. N-source effects on temporal distribution of NO_3-N leaching losses to subsurface drainage water. Water Air Soil Pollut. 181:35-50. doi: 10.1007/s11270-006-9274-z

Balesdent, J., J.R. Barlett, and H.E. Doner. 1988. Decomposition of lysine and leucine in soil aggregates: adsorption and compartmentalization. Soil Biol. Biochem., 20(1988), pp. 755-759

Balesdent, J., C. Chenu, and M. Balabane. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil and Tillage Research. Vol. 53 pgs. 215-230. https://doi.org/10.1016/S0167-1987(99)001017-5

Bean, G.M., N.R. Kitchen, J.J Camberato, R.B. Ferguson, F.G. Fernandez, D.W. Franzen, C.A.M. Laboski, E.D. Nafziger, J.E. Sawyer, P.C. Scharf, J. Schepers, and J.S. Shanahan. 2018. Improving an active-optical reflectance sensor algorithm using soil and weather information. Agron. J…..

Biggs, G.L., T.M. Blackmer, T.H. Demetriades-Shah, K.H. Holland, J.S. Schepers, and J.H. Wurm. 2002. Method and apparatus for real-time determination and application of nitrogen fertilizer using rapid, non-destructive crop canopy measurements. U.S. Patent 6,393,927. Date issued: 28 May.

Blackmer, A.M., G.D. Binford, T. Morris, and B. Meese. 1992 Effects of rates of nitrogen fertilization on corn yields, nitrogen losses from soils, and energy consumption. p. 2.1-2.6. In 1991 progress report of the intergrated farm management demonstration program. Iowa State Univ. Pm-1467

Blanchard, P.E. and R.N. Lerch. 2000. Watershed vulnerability to losses of agricultural chemicals: Interactions of chemistry, hydrology, and land-use. Environ. Sci. Technol. 34(16) pp 3315-3322. doi:10.1021/es991115+

Blevins D.W., D.H. Wilkison, B.P. Kelly, and S.R. Silva. 1996. Movement of nitrate fertilizer to glacial till and runoff from a claypan soil. J. Envir. Qual. 25:584-593. doi:10.2134/jeq1996.00472425002500030026x

Brown, K.H., M. E.A. Bach, R.A. Drijber, K.S. Hofmockel, E.S. Jeske, J.E. Sawyer, and M.J. Castellano. A long-term nitrogen fertilizer gradient has little effect on soil organic matter in a high-intensity maize production system. Global Change Biology. doi:10.1111/gcp.12519

Bu, H., L.K. Sharma, A. Denton, and D.W. Franzen. 2017. Comparison of satellite imagery and ground-based active optical sensors as yield predictors in sugar beet, spring wheat, corn, and sunflower. Agron. J. 109:299-308. doi:10.2134/agronj2016.03.0150

Chivenge, P., B. Vanlauwe, and J. Six. 2011. Does the combined application of organic and mineral nutrient sources infuence maize productivity? Plant Soil 342: 1-30. doi:10.1007/s11104-010-0626-5

Crowther, J.D. Integrating management zones and canopy sensing to improve nitrogen recommendation algorithms. 2018. M.S. Thesis, Univ. of Nebraska, Lincoln, NE.

Curry, G.L., and B.L. Deuermeyer et al. 1989. Discrete simulation. Holden-Day, Oakland, CA

Davidson, E.A., and L.A. Janssens. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440: 165-173. doi: 10.1038/nature04514

Drohan P.J., E.J. Ciolkosz, G.W. Petersen. 2003. Soil survey mapping unit accuracy in forested field plots in northern pennsylvania. Soil Sci. Soc. Am. J. 67:208-214

Emmert, J.E. 2009. Using Canopy reflectance to monitor corn response to nitrogen and the effects of delayed nitrogen application. M.S. thesis., Purdue Univ., West Lafayette, IN.

Gehl, R.J., L.D. Maddux, and W.B. Gordon, and J.P. Schmidt. 2005. Corn yield response to nitrgoen rate and timing in sandy irrigated soils. Agron. J. 97:1230-1238. doi:10.2134/agronj2004.0303

Hoffman, F.O., and Hammonds, J.S. 1994. Propagation of uncertainty in risk assessments: the need to distinguish between uncertainties due to lack of knowledge and uncertainty due to variability. Risk Anal 14(5):707-712

Howard, D.M.., and P.J.A. Howard. 1993. Relationships between CO_2 evolution moisture content and temperature for a range of soils types. Soil Biol. Biochem. 25:1537-1546. doi:10.1016/0038-0717(93)90008-Y

IPNI. 2017. 4R nutrient stewardship. International plant nutrition institute. http://www.ipni.net/4R (accessed 3 Dec. 2018)

Jeutong, F., K.M. Eskridge, W.J. Waltman, and O.S. Smith. 2000. Comparison of bioclimatic indices for prediction of maize yields. Crop Sci. 40: 1612-1617

Kablan, L.A., V. Chabot, A. Mailloux, M. Bouchard, D. Fontaine, and T. Bruulsema. 2017. Variability in corn yield response to nitrogen fertilizer in Eastern Canada. Agron. J. 109:2231-2242. doi:10.2134/agronj2016.09.0511

Kern, J.S., M.G. Johnson. 1993. Conservation tillage on national soil and atmospheric carbon levels. Soil Sci. Am. J. 57(1993), pp. 200-210

Kitchen, N.R., K.A. Sudduth, S.T. Drummond, P.C. Scharf, H.L. Palm, D.F. Roberts, and E.D. Vories. 2010. Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. Agron. J. 102:71-84. doi:10.2134/agronj2009.0114

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

Kyveryga P.M., A.M. Blackmer, and F. Morris. 2007. Alternative benchmarks for economically optimum rates of nitrogen fertilization for corn. Agron. J. 99:1057-1065. doi: 10.2134/agronj2006.0340

Laird, D.A., and C.-W. Chang. 2013. Long-term impacts of residue harvesting on soil quality. Soil and Tillage Research. 134:33-40

Linn, D.M., and J.W. Doran. 1984. Effet of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci. Soc. Am. J. 48: 1267-1272. doi: 10.2136/sssaj1984.03615995004800060013x

Ma, B.L., T.Y. Wu, N. Tremblay, W. Dean, N.B. McLaughlin, M.J. Morrison, and G. Stewart. 2010. On-Farm assessment of the amount and timing of nitrogen fertilizer on ammonia volatilization. Agron. J. 102:134-144. doi:10.2134/agronj2009.0021

McCarty, G.W., J.J. Meisinger, and M.M Jenniskens. 1995. Relationships between total-N, biomass-N and active-N in soil under different tillage and N fertilizer treatments. Soil Biol. Biochem. 27(1995), pp. 1245-1250

Meisinger, J.J., J.S. Schepers, and W.R. Raun. 2008. Nitrogen in agricultural systems. p.563-612. American Society of Agronomny, Crop Science Society of America, Soil Science Society of America, 677 S. Segoe Rd., Madison, WI. doi: 10.2134/agronmonofr49.c14

Miller, E.C. 2012. Nitrogen application timing and rate effects on nitrogen utilization of corn and the adoption of active optical reflectance sensors for nitrogen management. M.S. Thesis, Purdue Univ., West Lafayette, IN.

Moebius-Clune, B.N., D.J. Moebius-Clune, B.K. Gugino, O.J. Idowu, R.R. Schindelbeck, A.J. Ristow,…G.S. Abawi. 2016. Comprehensive Assessment of Soil Health: The Cornell Framework Manual (3.1 ed.).

Moser, M.E. 2016. Residual effects of nitrogen fertilization on soil nitrogen pools and corn growth. M.S. Thesis, Purdue Univ., West Lafayette, IN.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In: Methods of Soil Analysis, Part 2, 2nd ed., A.L. Page et al., Ed. Agronomy. 9:961-1010. Am. Soc. of Agron., Inc. Madison, WI.

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

Power J.F., R. Weise, and D. Flowerday. 2001. Managing farming systems for nitrate control: A research review from managemetn systems evaluation areas. Environ. Quality J. 30: 1866-1880

Puntel, L.A., J.E. Sawyer, D.W. Barker, R. Dietzel, H. Poffenbarger, M.J. Castellano, K.J. Moore, P. Thorburn, and S.V. Archontoulis. 2016. Modeling long-term corn yield response to nitrogen rate and crop rotation. Front. Plant Sci. 7:1630. doi: 10.3389/fpls.2016.01630

Puntel, L.A., J.E. Sawyer, D.W. Barker, P. Thorburn, M.J. Castellano, K.J. Moore, A. VanLoocke, E.A. Heaton, and S.V. Archontoulis. 2018. A systems modeling approach to forecast corn economic optimum nitrogen rate. Front. Plant Sci. 9:436. doi: 10.3389/fpls.2018.00436

Randall, G.W., and J.A. Vetsch. 2005. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by fall and spring application of nitrogen and nitapyrin. J. Environ. Qual. 34:590-597. doi: 10.2134/agronj/jeq2005.0590.

Reeves, D.W., C.W. Wood, and J.T. Touchton. 1993. Timing nitrogen applications for cornin a winter legume conservation-tillage system. Agron. J. 85:98-106

Rykiel, E.J. 1996. Testing ecological models: the meaning of validation. Ecol. Model 90(3): 229-244

Sargent, R.G. 1984. A tutorial on verification and validation of stimulation models. In: proceedings fo the 1984 winter simulation conference. IEEE 84CH2098-2, Dallas, TX.

Sawyer, J., A. Mallarino, and R. Killorn. 2003. Take a good soil sample to help make good decisions. Iowa State University Extension. PM 287.

Saxton, K.E., and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70:1569-1578. doi:10.2136/sssaj2005.0117

Schaetzl, R., and S. Anderson. 2014 Soils Genesis and Geomorphology. 6th printing. Cambridge University Press, Cambridge, United Kingdom

Scharf, P.C. and J.A. Lory. 2002. Calibrating corn color from aerial photographs to predict sidedress nitrogen need. Agron. J. 94:397-404.

Scharf, P.C., N.R. Kitchen, K.A. Sudduth, J.G. Davis, V.C. Hubbard, and J.A. Lory. 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. Agron. J. 97:452-461. doi: 10.2134/agronj2005.0452

Scharf, P.C. and J.A. Lory. 2009. Calibrating reflectance measurements to predict optimal sidedress nitrogen rate for corn. Agron. J. 101:615-625. doi:10.2134/agronj2008.0111

Scharf P. C., D. K. Shannon, H. L. Palm, K. A. Sudduth, S. T. Drummond, N. R. Kitchen, L. J. Mueller, V. C. Hubbard, L. F. Oliveira. 2011. Sensor-based nitrogen application out-performed producer-chosen rates for corn in on-farm demonstrations. Agron. J. 103: 1683-1691. doi:10.2134/agronj2011.0164

Schröder, J.J., J.J. Neeteson, O. Oenema, and P.C. Stuik. 2000. Does the crop or soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crops Res. 66:151-164. doi:10.1016/S0378-42909(00)000-72-1

Shahandeh H., A.L. Wright, and F.M. Hons. 2011. Use of soil nitrogen parameters and texture for spatially-variable nitrogen fertilization. Precis. Agric. 12: 146-163. doi:10.1007/s11119-010-9163-8

Shanahan, J.F.. K. Holland, J.S. Shepers, D.D. Francis, M.R. Schlemmer, and R. Caldwell. 2003.Use of crp reflectance sensors to assess corn leaf chlorophyll content. p. 135-150. In T. VanToai et al. (ed.) Digital imaging and spectral techniques: Applications to precision agriculture and crop physiology. ASA Spec. Publ. 66. ASA, CSSA, and SSSA, Madison, WI.

Shanahan, J.F., N.R. Kitchen, W.R. Raun, and J.S. Schepers. 2008. Responsive in-season nitrogen management for cerals. Comput. Electron. Agric. 61:51-62. doi:10.1016/j.compag.2007.06.006

Sharma, L.K., S.K. Bali, A.A. Zaeen, P. Baldwin, and D.W. Franzen. 2018. Use of rainfall data to improve ground-based active optical sensors yield estimates. Agron. J. 110:1561-1571. doi: 10.2134/agronj2017.12.0696

Shaw, L.H. 1964. The effect of wether on agricultural output: A look at the methodology. J. Farm Econ. 46:218-230

Soil Survey Staff, 2014. Kellogg Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 5.0. R. Burt and Soil Survey Staff (ed.). U.S. Department of Agriculture, Natural Resources Conservation Service.

Sylvia, D.M., J.J. Fuhrmann, P.G. Hartel., and D.A. Zuberer. Principles and Applications of Soil Microbiology. 2005. 2nd Ed. Prentice Hall, Upper Saddle River, New Jersey

Tonitto, C., P.B. Woodbury, and E.L. McLellan. 2018. Defining a best practice methodology for modeling the environmental performance of agriculture. Environ. Sci. and Pol. Vol. 87:64-73. https://doi.org/10.1016/j.envsci.2018.04.009

Tremblay, N., 2004. Determining nitrogen requirements from crops characteristics: benefits and challenges. Recent res. Dev. Agron. Hortic. 1:157-182

Tremblay, N., and C. Belec. 2006. Adapting nitrogen fertilization to unpredictable seasonal conditions with the least impact on the environment. Hort-Technology 16:408-412

Tremblay, N., M.Y. Bouroubi, B. Panneton, S. Guillaume, and P. Vigneault. 2011. Guidelines for in-season nitrogen application for maize (Zea mays L.) based on soil and terrain properties. Field Crops Res. 122:273-283. doi:10.1016/j.fcr.2011.04.008

Tremblay N., Y. M. Bouroubi, C. Belec, R. W. Mullen, N. R. Kitchen, W. E. Thomason, S. Ebelhar, D. B. Mengel, W. R. Raun, D. D. Francis, E. D. Vories, and I. O. Monasterio. 2012. Corn response to nitrogen is influenced by soil texture and weather. Agron. J. 104:1658-1671. doi: 10.2134/agronj2012.0184

Ullah, S. and T.R. Moore. 2009. Soil drainage and vegetation controls of nitrogen transformation rates in forest soils, southern Quebec. J. Geophys. Res. Biogen. doi:10.1029/2008jg000824

Weil, R.R., and N.C. Brady. 2017. Nature and property of soils. The 15th edition. Upper Saddle River, NJ. Prentice Hall.

Williams, J.D., C.R. Cozier, J.G. White, R.W. Heiniger, R.R. Sripada, and D.A. Crouse. 2007. Illinois soil nitrogen test predicts southeastern US corn economic optimum nitrogen rates. Soil Sci. Soc. Am J. 71:735-744. doi:10.2136/sssaj2006.0135

Xie M., N. Tremblay, G. Tremblay, G. Bourgeois, M.Y. Bouroubi, and Z. Wei. 2013. Weather effects on corn response to in-season nitrogen rates. Can, J. Plant Sci. 93:407-417. doi:10.4141/CJPS2012-145

Yamoah C.F., G.E. Varvel, C. Francis, and W. Waltman. 1998. Weather and management impact on crop yield variability in rotations. J. Prod. Agric. 11: 219-225. doi: 10.2134/jpa1998.0219

Zibilske, L.M. 1994. Carbon mineralization. In: Weaver RW, Angle JS, Bottomley PS 9eds) Methods of Soil Analysis, Part 2. Microbiological and Biochemical Properties. Soil Sci. Soc. Am., Madison WI, pp 835-864

Zhu, Q., J.P. Schmidt, H.S. Lin, and R.P. Sripada. 2009. Hydropedological processes and their implications for nitrogen availability to corn. Geoderma 154:111-122. doi:10.1016/J.geoderma.2009.10.004

4.7 Tables and Figures

Table 4.1. A list and brief description of the outside datasets used in this 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 carbon, crop yield in varying corn cropping systems, and corn model development	68	Brown et al., 2014; Puntel et al., 2016; Poffenbarger et al., 2017; Puntel et al., 2018;
IN	Corn N response studies at several Purdue University Agricultural centers focused on fertilizer application timing, rate and residual effects, and canopy reflectance	67	Emmert et al., 2009; Miller et al., 2012; Moser et al., 2016
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 et al., 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	13	Bu et al., 2017; Sharma et al., 2018

Table 4.2. Soil characteristics for all 182 site-years. Validation N response data was collected from six U.S. Midwest Corn Belt states. Hydrologic soil group and drainage classification information was gathered to delineate each site-year into one of five groups. Within each delineated group site-years were separated by N time (1 = N applied at-planting; 2 = N applied at side-dress). Other variables measured for each site-year included soil organic matter in the top 30 and 60 cm (SOM 30; SOM 60) of soil, total carbon (TC) and soil respiration in the top 30 cm of soil, percent clay in the top 30 and 60 cm of soil (clay 30; clay 60), SSURGO plant available water (SRGO PAWC 60, and the evenness of rainfall from the time of planting to the time of rainfall (SDI).

Year	State	Site	Field	Group Delineation	N App Time	SOM 30	SOM 60	TC	Soil Respiration	Clay 30	Clay 60	PAWC 30	SRGO PAWC 60	SDI
						-----%-----			mg kg^{-1} soil	----------%---------			cm 30 cm^{-1}	
1999	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2000	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2001	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2002	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2003	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2004	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2005	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2006	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2007	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2008	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2009	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2010	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2011	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2012	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2013	IA	Central	C	2	2	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	0.683
2014	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2015	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.
2016	IA	Central	C	2	1	3.1	2.3	1.8	108	26.3	27.9	0.14	5.49	.

2000	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2001	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2002	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2003	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2004	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2005	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2006	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2007	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2008	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2009	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2010	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2011	IA	Northwest	NW	1	2	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	0.63
2012	IA	Northwest	NW	1	2	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	0.53
2013	IA	Northwest	NW	1	1	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	.
2014	IA	Northwest	NW	1	2	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	0.42
2015	IA	Northwest	NW	1	2	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	0.66
2016	IA	Northwest	NW	1	2	4.3	2.8	2.5	100	38.5	37.5	0.17	6.19	0.67
1999	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.51
2000	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.40
2001	IA	South	S	5	1	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	.
2002	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.65
2003	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.47
2004	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.65
2005	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.47
2006	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.60
2007	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.57
2008	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.30
2009	IA	South	S	5	1	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	.
2010	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.71
2011	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.59
2012	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	.
2013	IA	South	S	5	2	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	0.64

2014	IA	South	S	5	1	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	.
2015	IA	South	S	5	1	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	.
2016	IA	South	S	5	1	3.1	2.2	2.0	87	26.1	35.8	0.21	5.12	.
1999	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2000	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2001	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2002	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2003	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2004	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2005	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2006	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2007	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2008	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2009	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2010	IA	Southeast	SE	5	2	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	0.55
2011	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2012	IA	Southeast	SE	5	2	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	0.25
2013	IA	Southeast	SE	5	2	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	0.63
2014	IA	Southeast	SE	5	2	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	0.55
2015	IA	Southeast	SE	5	2	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	0.69
2016	IA	Southeast	SE	5	1	3.9	3.0	2.6	96	37.4	41.5	0.17	5.43	.
2006	IN	ACRE	93	1	2	3.1	2.0	1.9	94	27.4	33.3	0.17	6.19	0.73
2007	IN	ACRE	92	3	2	3.5	2.1	2.1	119	30.8	32.8	0.17	6.19	0.50
2007	IN	ACRE	94	5	2	.	.	.	.	36.9	37.9	.	5.80	0.50
2008	IN	ACRE	93	1	2	3.1	2.0	1.9	94	27.4	33.3	0.17	6.19	0.66
2008	IN	ACRE	94	5	2	.	.	.	.	36.9	37.9	.	5.80	0.66
2009	IN	ACRE	92	3	2	3.5	2.1	2.1	119	30.8	32.8	0.17	6.19	0.48
2009	IN	ACRE	94	5	2	.	.	.	.	36.9	37.9	.	5.80	0.48
2010	IN	ACRE	93	1	2	3.1	2.0	1.9	94	27.4	33.3	0.17	6.19	0.67
2010	IN	ACRE	94	5	2	.	.	.	.	36.9	37.9	.	5.80	0.67
2011	IN	ACRE	92	3	2	3.5	2.1	2.1	119	30.8	32.8	0.17	6.19	0.55
2012	IN	ACRE	93	1	2	3.1	2.0	1.9	94	27.4	33.3	0.17	6.19	0.54

2012	IN	ACRE	93	3	1	3.1	2.0	1.9	94	27.4	33.3	0.17	6.19	.
2013	IN	ACRE	92	3	2	3.5	2.1	2.1	119	30.8	32.8	0.17	6.19	0.58
2013	IN	ACRE	92	3	1	3.5	2.1	2.1	119	30.8	32.8	0.17	6.19	.
2014	IN	ACRE	93	1	2	3.1	2.0	1.9	94	27.4	33.3	0.17	6.19	0.54
2015	IN	ACRE	92	3	2	3.5	2.1	2.1	119	30.8	32.8	0.17	6.19	0.45
2006	IN	DPAC	N	5	2	.	.	.	.	43.6	52.6	.	4.58	0.43
2007	IN	DPAC	M1	1	2	.	.		.	43.6	52.6	.	4.58	0.51
2007	IN	DPAC	M2	1	2	2.6	1.8	1.4	154	33.0	42.5	0.16	4.58	0.51
2008	IN	DPAC	M1	1	2	.	.	.	.	43.6	52.6	.	4.58	0.47
2008	IN	DPAC	P	5	2	2.4	2.0	1.5	200	32.8	41.1	0.16	4.58	0.47
2009	IN	DPAC	M1	1	2	.	.	.	.	43.6	52.6	.	4.58	0.61
2009	IN	DPAC	M1	1	2	.	.	.	.	43.6	52.6	.	4.58	0.61
2009	IN	DPAC	M1	1	2	.	.	.	.	43.6	52.6	.	4.58	0.61
2009	IN	DPAC	M2	1	2	2.6	1.8	1.4	154	33.0	42.5	0.16	4.58	0.61
2011	IN	DPAC	M2	1	2	2.6	1.8	1.4	154	33.0	42.5	0.16	4.58	0.46
2012	IN	DPAC	P	5	2	2.4	2.0	1.5	200	32.8	41.1	0.16	4.58	0.48
2012	IN	DPAC	P	5	1	2.4	2.0	1.5	200	32.8	41.1	0.16	4.58	.
2013	IN	DPAC	M2	1	2	2.6	1.8	1.4	154	33.0	42.5	0.16	4.58	0.54
2013	IN	DPAC	M2	1	1	2.6	1.8	1.4	154	33.0	42.5	0.16	4.58	.
2014	IN	DPAC	P	5	2	2.4	2.0	1.5	200	32.8	41.1	0.16	4.58	0.63
2014	IN	DPAC	P	5	1	2.4	2.0	1.5	200	32.8	41.1	0.16	4.58	.
2015	IN	DPAC	M2	1	2	2.6	1.8	1.4	154	33.0	42.5	0.16	4.58	0.65
2006	IN	PPAC	A4	3	2	3.0	1.9	1.7	110	21.9	26.9	0.13	5.19	0.65
2007	IN	PPAC	B4	3	2	.	.	.	.	32.3	28.9	.	5.19	0.51
2007	IN	PPAC	C4	3	2	3.8	1.6	2.1	106	26.2	23.1	0.15	5.19	0.51
2007	IN	PPAC	C4	3	2	3.8	1.6	2.1	106	26.2	23.1	0.15	5.19	0.51
2008	IN	PPAC	A4	3	2	3.0	1.9	1.7	110	21.9	26.9	0.13	5.19	0.53
2008	IN	PPAC	B4	3	2	.	.	.	.	32.3	28.9	.	5.19	0.53
2009	IN	PPAC	B4	3	2	.	.	.	.	32.3	28.9	.	5.19	0.45
2009	IN	PPAC	C4	3	2	3.8	1.6	2.1	106	26.2	23.1	0.15	5.19	0.45
2009	IN	PPAC	M2	2	2	1.6	0.9	0.8	73	11.7	13.2	0.11	4.27	0.61
2009	IN	PPAC	M2	2	1	1.6	0.9	0.8	73	11.7	13.2	0.11	4.27	.

2010	IN	PPAC	A4	3	2	3.0	1.9	1.7	110	21.9	26.9	0.13	5.19	0.67
2010	IN	PPAC	B4	3	2	.	.	.	.	32.3	28.9	.	5.19	0.67
2011	IN	PPAC	C4	3	2	3.8	1.6	2.1	106	26.2	23.1	0.15	5.19	0.61
2011	IN	PPAC	C4	3	1	3.8	1.6	2.1	106	26.2	23.1	0.15	5.19	.
2011	IN	PPAC	E1	4	2	.	.	.	.	32.3	28.9	.	2.75	0.27
2012	IN	PPAC	A4	3	2	3.0	1.9	1.7	110	21.9	26.9	0.13	5.19	0.27
2012	IN	PPAC	A4	3	1	3.0	1.9	1.7	110	21.9	26.9	0.13	5.19	.
2012	IN	PPAC	I6	3	2	2.8	1.3	1.7	102	14.7	18.3	0.13	5.19	0.61
2012	IN	PPAC	I6	3	1	2.8	1.3	1.7	102	14.7	18.3	0.13	5.19	.
2013	IN	PPAC	C4	3	2	3.8	1.6	2.1	106	26.2	23.1	0.15	5.19	0.61
2013	IN	PPAC	C4	3	1	3.8	1.6	2.1	106	26.2	23.1	0.15	5.19	.
2013	IN	PPAC	D-South	3	2	10	3.7	7.3	418	27.0	5.2	0.18	5.19	0.45
2013	IN	PPAC	D-South	3	1	10	3.7	7.3	418	27.0	5.2	0.18	5.19	.
2014	IN	PPAC	A4	3	2	3.0	1.9	1.7	110	21.9	26.9	0.13	5.19	0.66
2014	IN	PPAC	A4	3	1	3.0	1.9	1.7	110	21.9	26.9	0.13	5.19	.
2014	IN	PPAC	M1	2	2	1.7	1.1	0.9	73	12.1	14.7	0.12	4.27	0.66
2014	IN	PPAC	M1	2	1	1.7	1.1	0.9	73	12.1	14.7	0.12	4.27	.
2015	IN	PPAC	C4	3	2	3.8	1.6	2.1	106	26.2	23.1	0.15	5.19	0.54
2006	IN	SWPAC	23	2	2	1.3	1.1	0.8	92	9.0	10.6	0.10	5.19	0.57
2007	IN	SWPAC	20	1	2	1.1	0.6	0.6	43	7.1	7.0	0.07	5.49	0.49
2008	IN	SWPAC	23	2	2	1.3	1.1	0.8	92	9.0	10.6	0.10	5.19	0.54
2009	IN	SWPAC	18	1	2	1.1	0.8	0.7	48	9.3	11.2	0.09	2.85	0.61
2010	IN	SWPAC	20	1	2	1.1	0.6	0.6	43	7.1	7.0	0.07	5.49	0.73
2011	IN	SWPAC	23	2	2	1.3	1.1	0.8	92	9.0	10.6	0.10	5.19	0.43
2013	IN	SWPAC	23	2	2	1.3	1.1	0.8	92	9.0	10.6	0.10	5.19	0.54
2014	IN	SWPAC	20	1	2	1.1	0.6	0.6	43	7.1	7.0	0.07	5.49	0.62
2004	MO	Wilson	North	1	2	2.6	1.9	1.3	94	32.5	48.2	0.18	3.66	0.67
2004	MO	Wilson	South	1	2	2.3	2.2	1.3	64	22.5	44.8	0.21	4.43	0.67
2006	MO	Gebhardt	summit	4	2	2.0	1.6	1.0	52	22.1	29.3	0.21	6.59	0.53
2006	MO	Gebhardt	Toe	4	2	1.9	1.4	0.9	37	21.9	27.3	0.21	5.80	0.53
2007	MO	Gebhardt	House	4	2	2.0	1.3	1.1	50	17.7	19.2	0.22	6.57	0.54
2016	NE	AR	3	1	2	3.1	2.2	1.7	50	37.0	41.2	0.17	5.29	0.47

2016	NE	AR	8	1	2	3.6	2.0	2.2	44	28.6	25.4	0.20	4.55	0.47
2016	NE	HU	6	4	2	2.2	1.5	1.2	58	32.0	32.4	0.18	5.31	0.63
2016	NE	HU	14	4	2	1.4	0.9	0.6	92	29.2	27.5	0.18	5.19	0.63
2016	NE	KR	12	2	2	0.8	0.8	0.4	18	3.5	5.5	0.05	5.19	0.66
2016	NE	KR	13	2	2	0.6	0.5	0.3	20	3.5	4.7	0.04	5.19	0.66
2017	NE	AR	7	4	2	2.9	2.7	1.6	41	32.8	37.5	0.18	4.88	0.59
2017	NE	AR	11	4	2	2.9	2.1	1.5	37	35.7	37.7	0.17	4.88	0.59
2017	NE	HU	5	4	2	2.9	2.5	1.7	50	25.4	31.9	0.19	5.31	0.86
2017	NE	HU	6	4	2	2.8	2.4	1.7	43	23.1	28.4	0.20	5.31	0.86
2017	NE	JA	11	1	2	1.6	1.0	1.0	29	8.1	7.6	0.09	3.05	0.66
2017	NE	JA	12	1	2	1.4	1.0	0.9	22	7.7	6.7	0.09	3.05	0.66
2017	NE	KR	3	1	2	1.6	0.6	0.7	23	5.9	4.3	0.07	2.47	0.56
2017	NE	KR	4	1	2	1.2	0.4	0.7	43	5.9	2.7	0.07	2.47	0.56
2010	ND	Embden	Embden	4	1	1.9	.	1.2	159	14.8	.	0.09	5.10	.
2010	ND	Hankinson	Hankinson	4	1	3.7	.	2.5	121	22.1	.	0.14	5.75	.
2010	ND	Prosper	Prosper	5	1	2.3	.	1.7	146	23	.	0.13	5.49	.
2010	ND	Prosper#2	Prosper#2	1	1	3.7	.	2.6	114	38.9	.	0.16	5.49	.
2010	ND	Walcott	Walcott	3	1	1.7	.	1.7	152	11.5	.	0.06	3.66	.
2011	ND	Arthur	Arthur	5	1	2.3	.	1.5	140	18.9	.	0.11	4.79	.
2011	ND	Fairmont	Fairmont	1	1	2.9	.	2.4	132	6.7	.	0.24	5.57	.
2011	ND	Valley City	Valley City	2	1	3.8	.	2.3	161	23.2	.	0.14	5.29	.
2012	ND	Arthur	Arthur	5	1	1.8	0.8	1.5	157	13.7	3.2	0.08	0.00	.
2012	ND	Mooreton	Mooreton	3	1	0.8	.	1.1	171	4.8	.	0.07	3.66	.
2012	ND	Walcott	Walcott	3	1	2.5	.	2.3	147	4.5	.	0.10	4.01	.
2013	ND	Gardner	Gardner	5	1	2.0	.	1.4	145	15.1	.	0.09	4.58	.
2014	WI	NTIME	LAN	2	1	1.9	1.3	0.9	129	22.6	28.8	0.21	5.80	.
2014	WI	NTIME	LAN	2	2	1.9	1.3	0.9	129	22.6	28.8	0.21	5.80	0.54
2014	WI	NTIME	MAR	1	1	2.4	0.9	1.2	142	15.3	23.2	0.20	6.10	.
2014	WI	NTIME	MAR	1	2	2.4	0.9	1.2	142	15.3	23.2	0.20	6.10	0.65
2015	WI	NTIME	LAN	2	1	2.0	1.3	1.1	.	19.2	27.4	0.21	5.80	.
2015	WI	NTIME	LAN	2	2	2.0	1.3	1.1	.	19.2	27.4	0.21	5.80	0.63
2015	WI	NTIME	MAR	1	1	2.5	1.0	1.4	133	18.9	21.9	0.20	6.10	.

2015	WI	NTIME	MAR	1	2	2.5	1.0	1.4	133	18.9	21.9	0.20	6.10	0.69
2016	WI	MCOV	ARL	2	2	4.5	2.4	2.8	219	25.0	26.1	0.21	5.80	0.63
2016	WI	MCOV	MAR	1	2	2.5	1.2	1.4	154	18.1	19.5	0.20	6.10	0.69
2016	WI	NTIME	LAN	2	1	1.7	1.1	0.9	.	23.2	29.9	0.21	5.80	.
2016	WI	NTIME	LAN	2	2	1.7	1.1	0.9	.	23.2	29.9	0.21	5.80	0.61
2016	WI	NTIME	MAR	1	1	2.7	1.3	1.5	157	16.2	20.3	0.20	6.10	.
2016	WI	NTIME	MAR	1	2	2.7	1.3	1.5	157	16.2	20.3	0.20	6.10	0.69
2017	WI	MCOV	ARL	2	2	3.9	3.5	2.2	178	25.5	27.5	0.21	5.80	0.63
2017	WI	MCOV	MAR	1	2	3.1	1.2	1.7	154	19.0	20.3	0.21	6.10	0.67
2018	WI	MCOV	ARL	2	2	2.1	3.2	0.9	125	30.4	26.3	0.18	5.80	0.68
2018	WI	MCOV	MAR	1	2	2.4	1.5	1.3	113	16.6	21.2	0.21	6.10	0.42

Table 4.3 United States Department of Agriculture’s defined hydrologic soil groups (HG). The HG 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 an HG, the least transmissive layer is used.

Hydrologic group	Runoff	Water transmission	Soil texture	K_{SAT}	Depth to water table	Depth to impermeable layer
				cm hr^{-1}	----------------cm	------------------------
A	Low	Unrestricted	>90% sand and <10% clay	>14.5	>61	>51
B	Mod. Low	Unrestricted	10-20% clay and 50-90% sand	3.6-14.5	>61	>51
C	Mod. 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 4.4. The United States Department of Agriculture's drainage classifications. Seven classes of natural drainage have been defined and refer to the frequency and duration of wet periods similar to those in which the soil formed. It should be noted that human modifications to drainage or irrigation were not considered in these classifications unless they greatly influenced the morphology of the soil.

Drainage Class	USDA Description
Excessively drained	- Water removed rapidly - Internal free water is very rare or deep - Coarse-textured soils with very high K_{SAT}
Somewhat excessively drained	- Water removed rapidly - Internal free water is rare or deep - Coarse-textured soils with high K_{SAT}
Well drained	- Water removed readily but not rapidly - Internal free water is deep to very deep - Water is available to plants for most of the growing season (in humid areas) - Wetness does not prevent growth of roots for prolonged periods of time - Mainly free from redoximorphic features
Moderately well drained	- Water is removed from the soil somewhat slowly throughout different times of the year - Internal free water is moderately deep and transitory - Soils are wet within the rooting zone for only a short time during the growing season but long enough for mesophytic plants to be affected - Periodically receive high rainfall - Low K_{SAT} within upper 1 m of soil - Periodically receives high rainfall
Somewhat poorly drained	- Water is removed slowly - Soil is wet at shallow depths for a significant amount of time during the growing season - Internal free water is hallow to moderately deep and transitory to permanent - Wetness restricts the growth of mesophytic plants - Usually have either low to very low K_{SAT}, a high water table, continuous rainfall, or additional water seepage
Poorly drained	- Water is removed slowly - Soil is wet at shallow depths periodically or remains wet for much of the growing season - Internal free water is shallow or very shallow and common or persistent - Free water is found at or near the surface for long periods of time throughout the growing season - Mesophytic plants cannot be grown unless artificially drained

Very poorly drained	- The soil is not continuously wet below the plow layer - Shallow water table is a result of low or very low K_{SAT} or continuous rainfall - Water is removed very slowly - Standing water for much of the growing season - Internal free water is very shallow and is persistent or permanent - Most mesophytic plants cannot be grown unless artificially drained - Soils are commonly level or depressed and frequently have standing water

Table 4.5. A list, brief description, and the calculation used to determine the state-specific corn N fertilizer recommendation for IA, IN, MO, NE, ND, and WI.

State	Corn N recommendation approach	Calculation	Reference
IA, IN, ND, WI	Maximum Return to Nitrogen (MRTN): a series of corn N response models derived from years of N response trials unique to a designated area or region. Each year area appropriate corn N response trials, where yield response is empirically modeled as a function of N rate, are used to regularly adjust MRTN. Adjustments can also be made based on corn and fertilizer prices.	- No available calculation.	Sawyer et al., 2006
MO	Yield Goal (YG): A calculation in which an expected yield, the N supplying ability of the soil (based on soil organic matter and cation exchange capacity), plant population, and a 34 kg N ha^{-1} soybean credit are used to determine corn N need.	$Nrec = 1.12 \times [0.9 \times YG + 4 \times Plant\ population - SOMcredit - Ncredit$	Brown et al., 2004
NE	Yield Goal (YG): A calculation which includes expected yield, soil inorganic nitrate (measured or estimated), potential N mineralized from soil organic matter, and a 39 or 50 kg N ha^{-1} soybean credit for sandy and non-sandy soils, respectively. Adjustments to this calculation can be made via soil texture and N fertilizer application time.	$Nrec = 1.12 \times [35 + (1.2 \times YG) - (8 \times Nitrate_{1.2\ m}) - 0.14 \times YG \times SOM - Ncredit] \times Ntime \times Price$	Shapiro et al., 2008

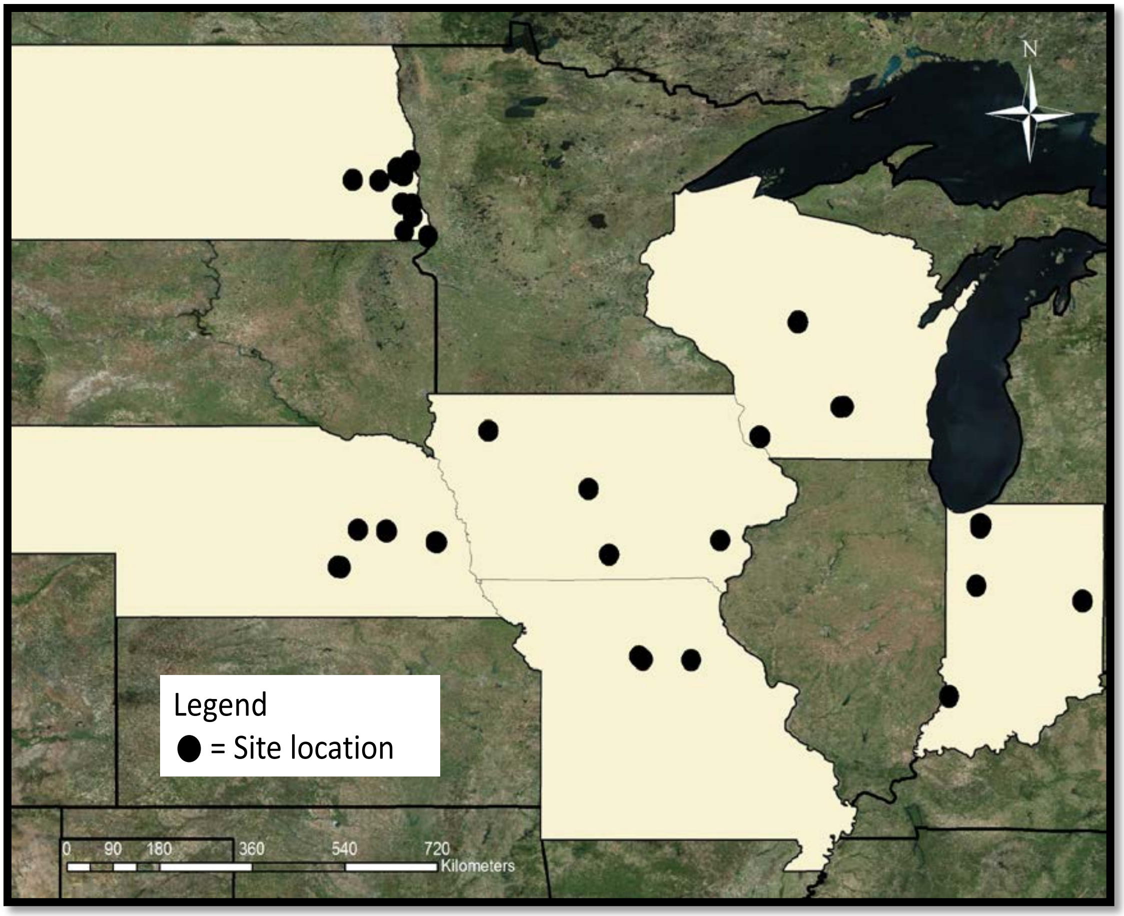

Figure 4.1. Field research sites were located within six U.S. Midwest Corn Belt states (Iowa, Indiana, Missouri, Nebraska, North Dakota, and Wisconsin).

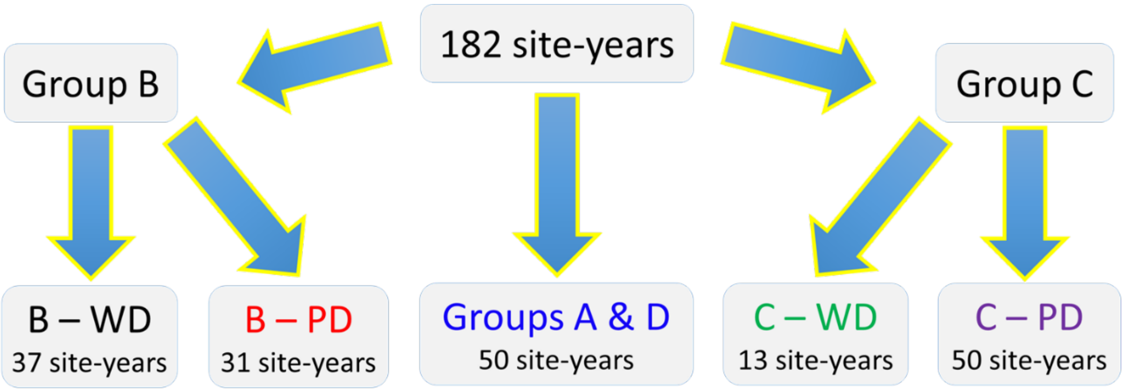

Figure 4.2. The delineation of all site locations using United States Department of Agriculture – Natural Resource Conservation Service (USDA-NRCS) define hydrologic soil group (HG) and drainage class. There are four total USDA-NRCS HG (A, B, C, D) with HG A having the least potential for runoff and HG D having the highest potential. Seven total USDA-NRCS drainage classifications have been defined, however for this analysis sites were considered either poorly-drained (PD) or well-drained (WD). Further information on HG or drainage class is found in Tables 4.3 and 4.4. Initial site delineation was made by using HG classification. Sites that fell within group A or D were combined. While these HG are opposite in definition, sites within these groups are most prone to N loss via leaching or denitrification. Drainage class was then used for the final delineation of sites. A total of 5 separate groups resulted.

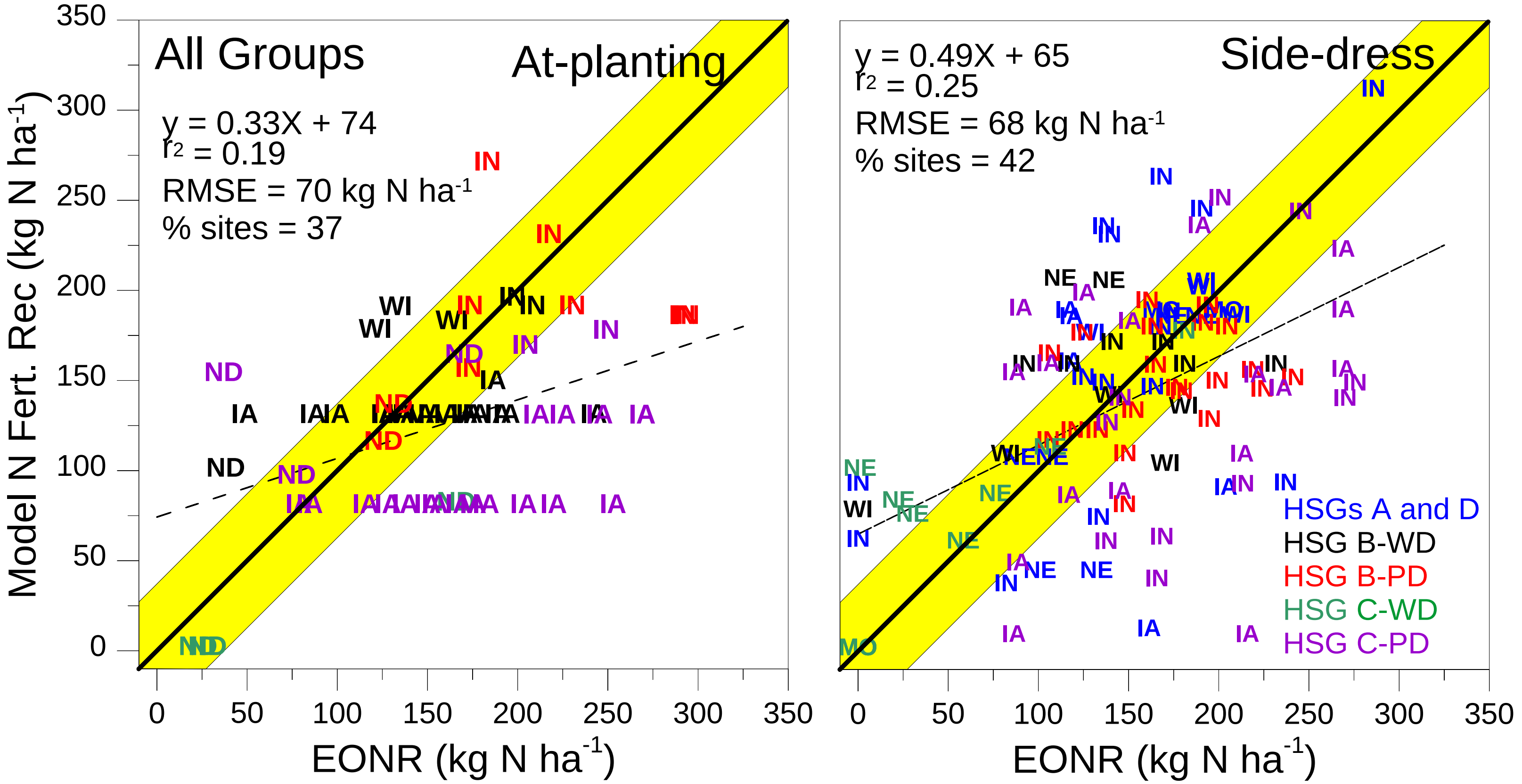

Figure 4.3. The economical optimum N fertilizer rate (EONR) compared to N recommendation models (N Fert. Rec) based on USDA-NRCS defined hydrologic soil groups (A, B, C, D) and drainage class (well-drained, WD; poorly-drained, PD) for both at-planting and side-dress N fertilizer timings. Sites within the yellow band are those within 34 kg N ha^{-1} of EONR. Overall, model N recommendations were better at side-dress. For the at-planting timing, no weather variables were included in the at-planting models since seasonal weather is not available at the time of planting. Also, for the at-planting N time, no soil variable was found significantly related to EONR for soils in the A and D hydrologic groups. Therefore, this approach is not applicable for soils where N is applied all at-planting.

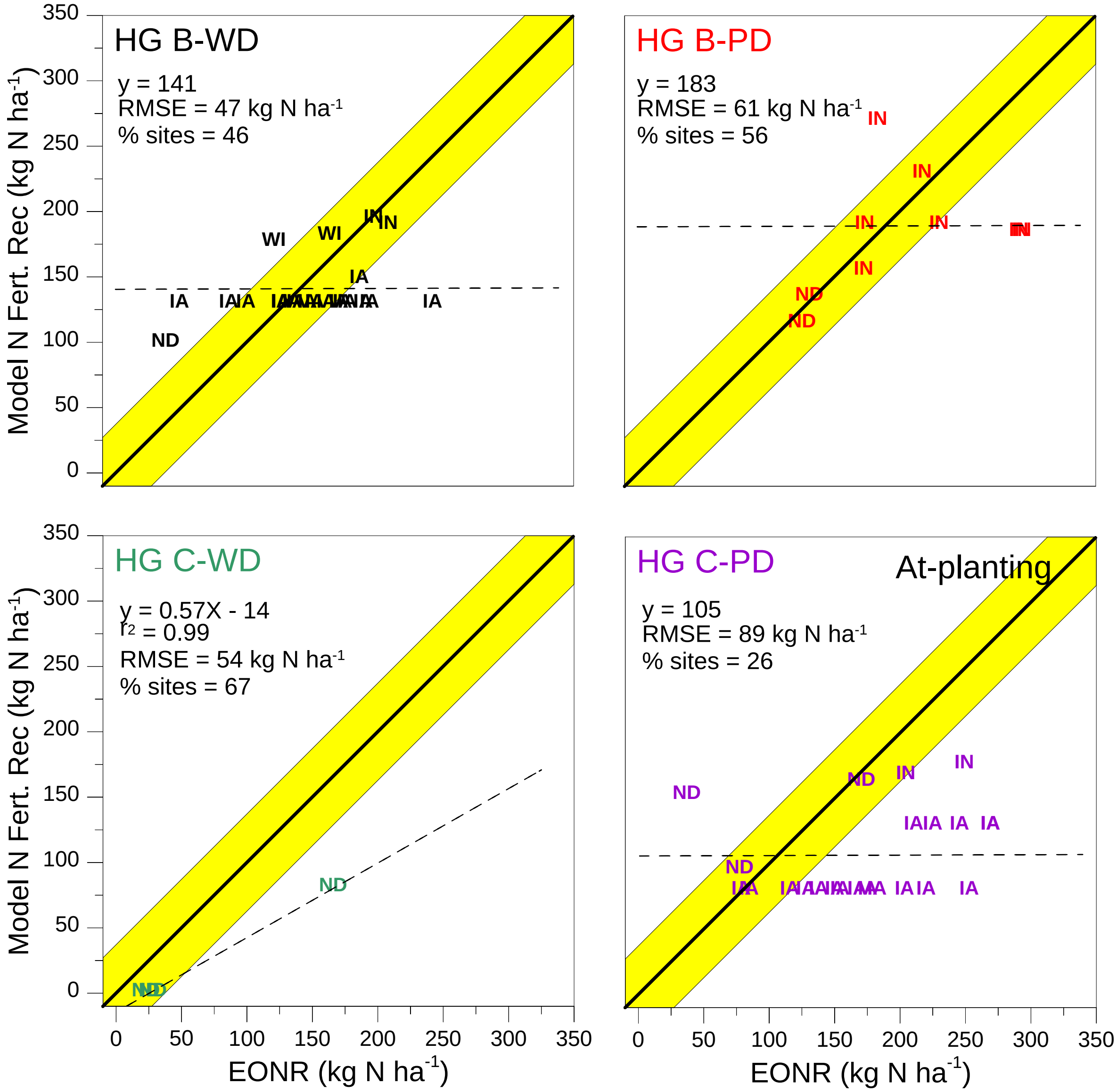

Figure 4.4. The economical optimum N fertilizer rate (EONR) compared to N recommendation models (N Fert. Rec) based on USDA-NRCS defined hydrologic soil groups (A, B, C, D) and drainage class (well-drained, WD; poorly-drained, PD) for the at-planting N fertilizer time. For non-significant relationships between the model recommendation and EONR the slope was set to zero and no r^2 reported. Sites within the yellow band are those within 34 kg N ha^{-1} of EONR. No weather variables were included in the at-planting models since seasonal weather is not available at the time of planting. Also, no soil variable was found significantly related to EONR for soils in the A and D hydrologic groups, therefore no graph was made.

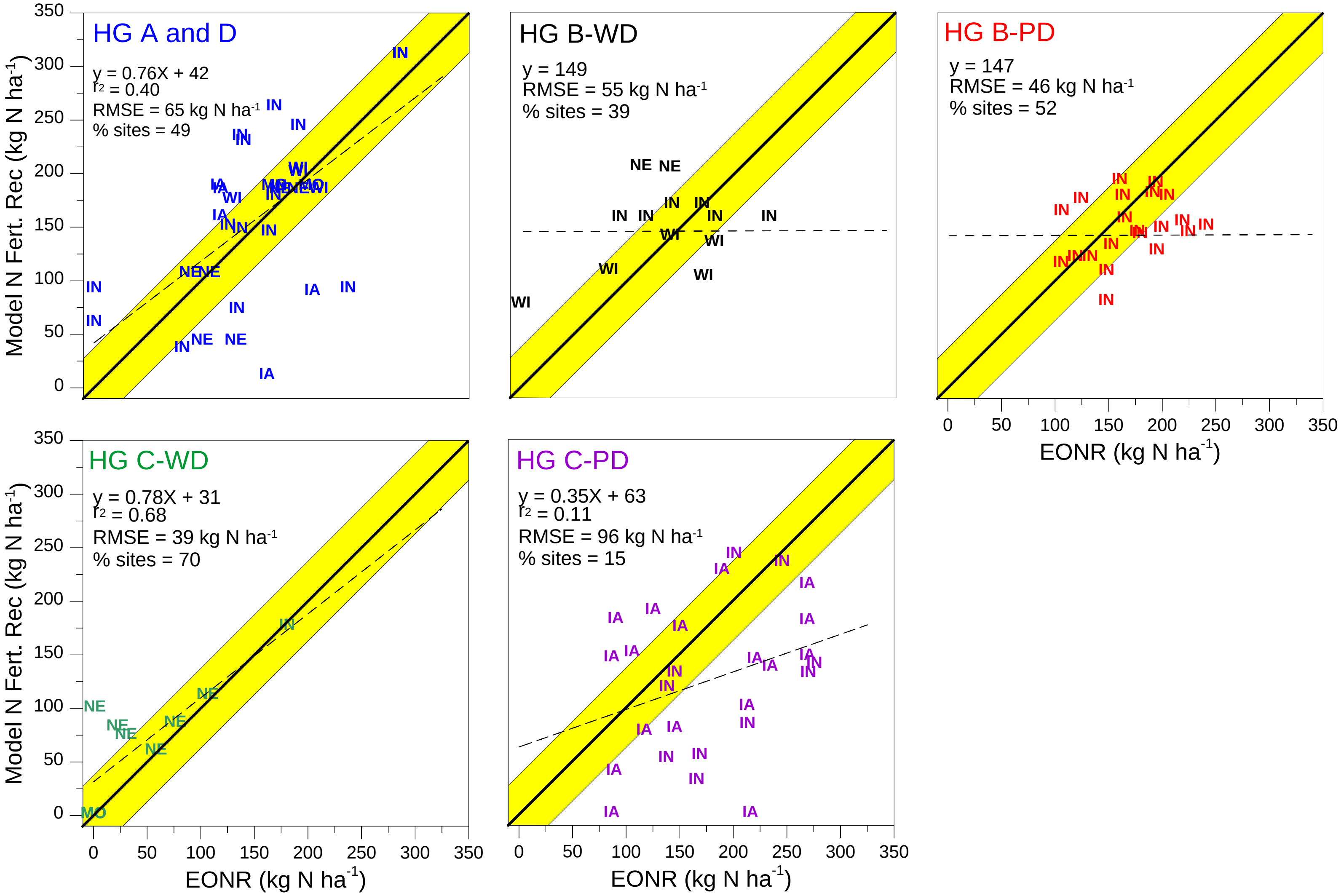

Figure 4.5. The economical optimum N fertilizer rate (EONR) compared to N recommendation models (N Fert. Rec) based on USDA-NRCS defined hydrologic soil groups (A, B, C, D) and drainage class (well-drained, WD; poorly-drained, PD) for the side-dress N fertilizer time. For non-significant relationships between the model recommendation and EONR the slope was set to zero and no r^2 reported. Sites within the yellow band are those within 34 kg N ha^{-1} of EONR.

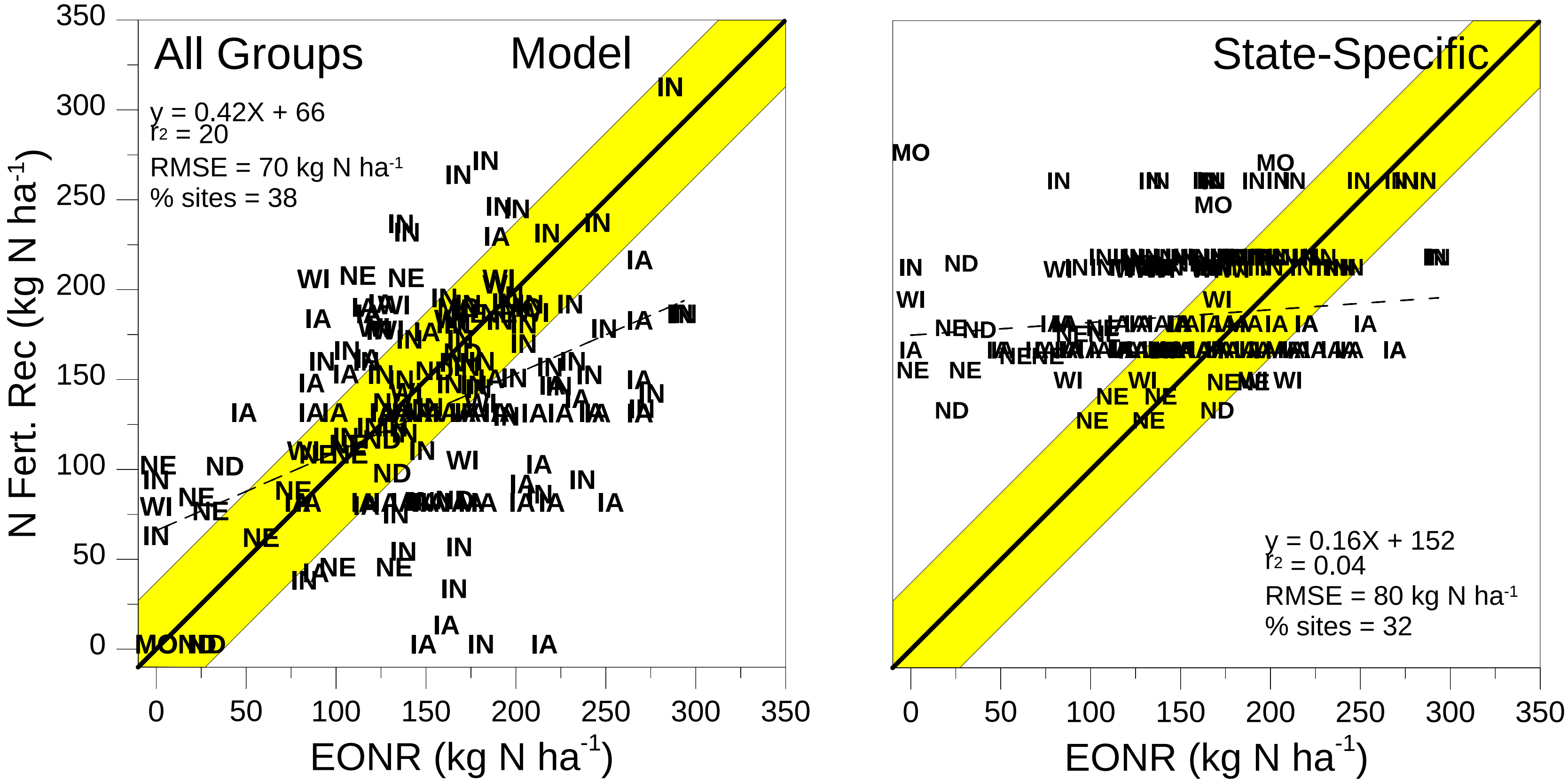

Figure 4.6. A comparison between the USDA hydrologic soil group based (HG-based) and state-specific N recommendation approaches. Four states in this analysis (IA, IN, ND, WI) employ the Maximum Return to Nitrogen Tool (MRTN) and two states the yield goal approach (MO, NE). For non-significant relationships between the model recommendation and EONR the slope was set to zero and no r^2 reported. Site-years that fall within the yellow band are those within 34 kg N ha^{-1} of EONR. Comparing across all 182 site-years revealed no significant difference between HG-based and state-specific N recommendation approaches. However, N responses (i.e., slopes) were found to be unique from one another suggesting the HG-based model was more sensitive to N need.

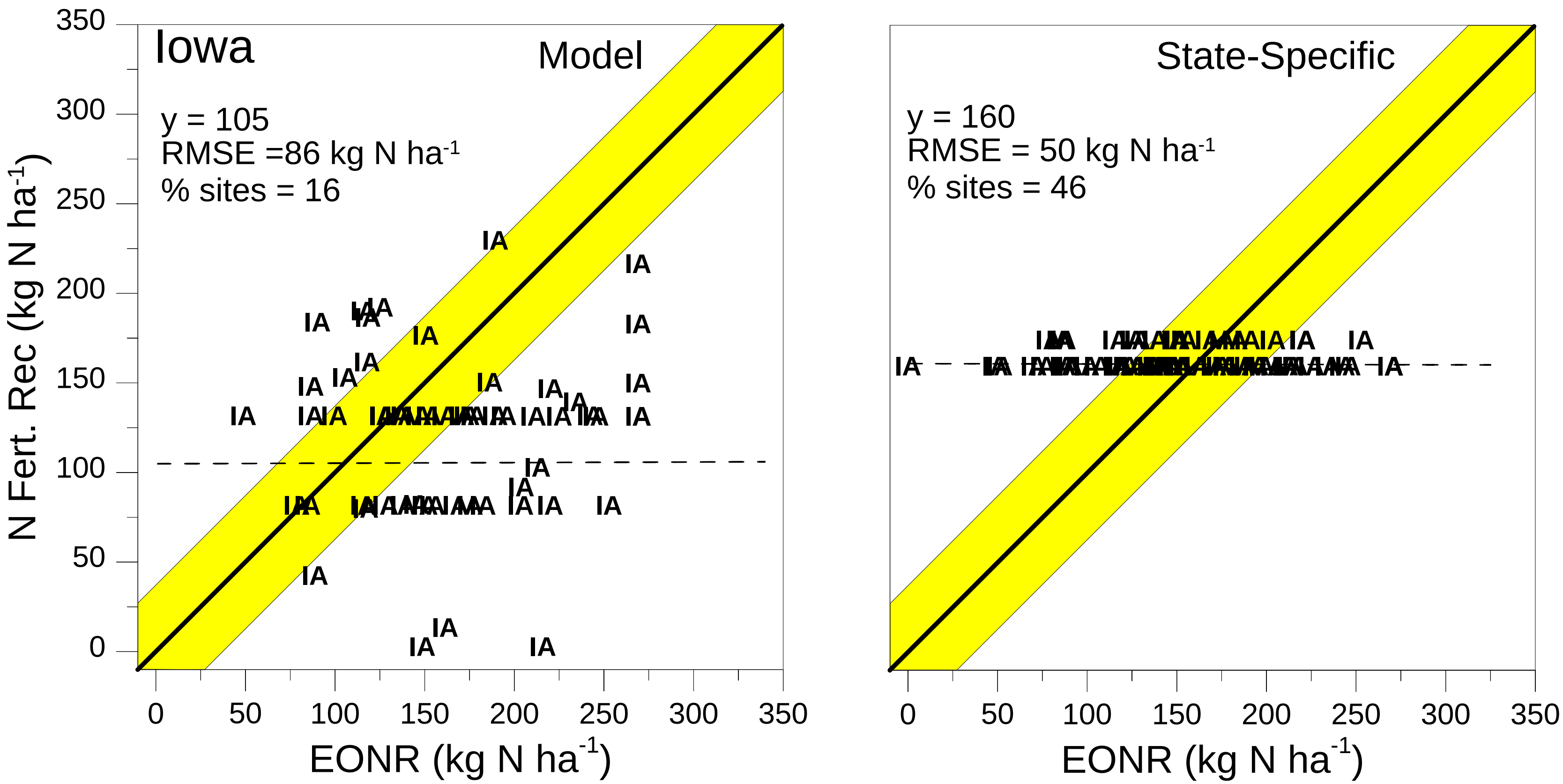

Figure 4.7.The hydrologic soil group (HG) based model N fertilizer recommendations for IA compared to the IA-specific Maximum Return to Nitrogen (MRTN) tool. For non-significant relationships between the model recommendation and EONR the slope was set to zero and no r^2 reported. Site-years that fall within the yellow band are within 34 kg N ha^{-1} of EONR. Overall, the IA-specific MRTN tool outperformed the HG-based model for estimating EONR.

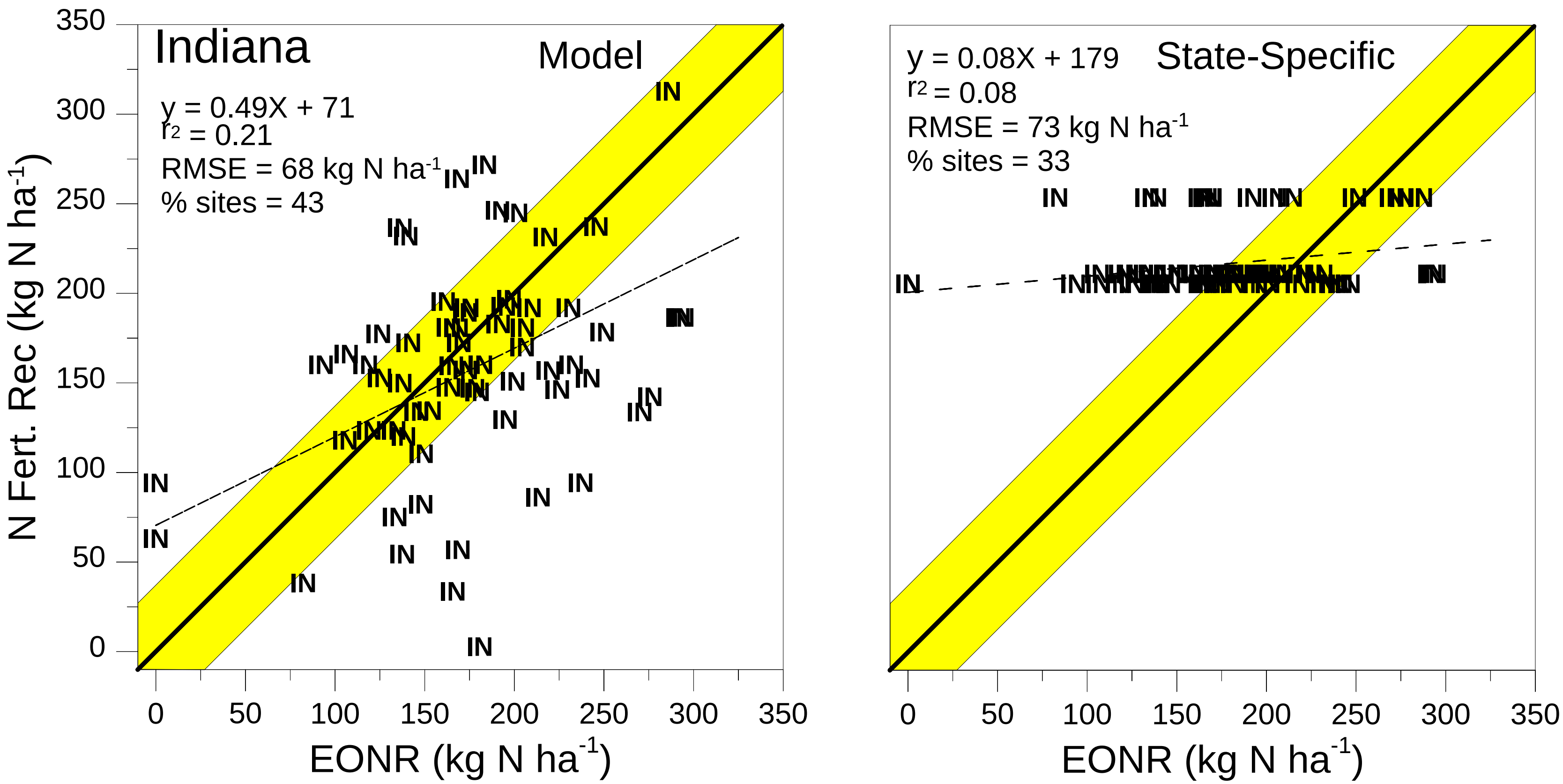

Figure 4.8. The hydrologic soil group (HG) based model N fertilizer recommendations for IN compared to the IN-specific Maximum Return to Nitrogen (MRTN) tool. For non-significant relationships between the model recommendation and EONR the slope was set to zero and no r^2 reported. Site-years that fall within the yellow band are within 34 kg N ha^{-1} of EONR. Overall, the HG-based model outperformed the IN-specific MRTN tool for estimating EONR.

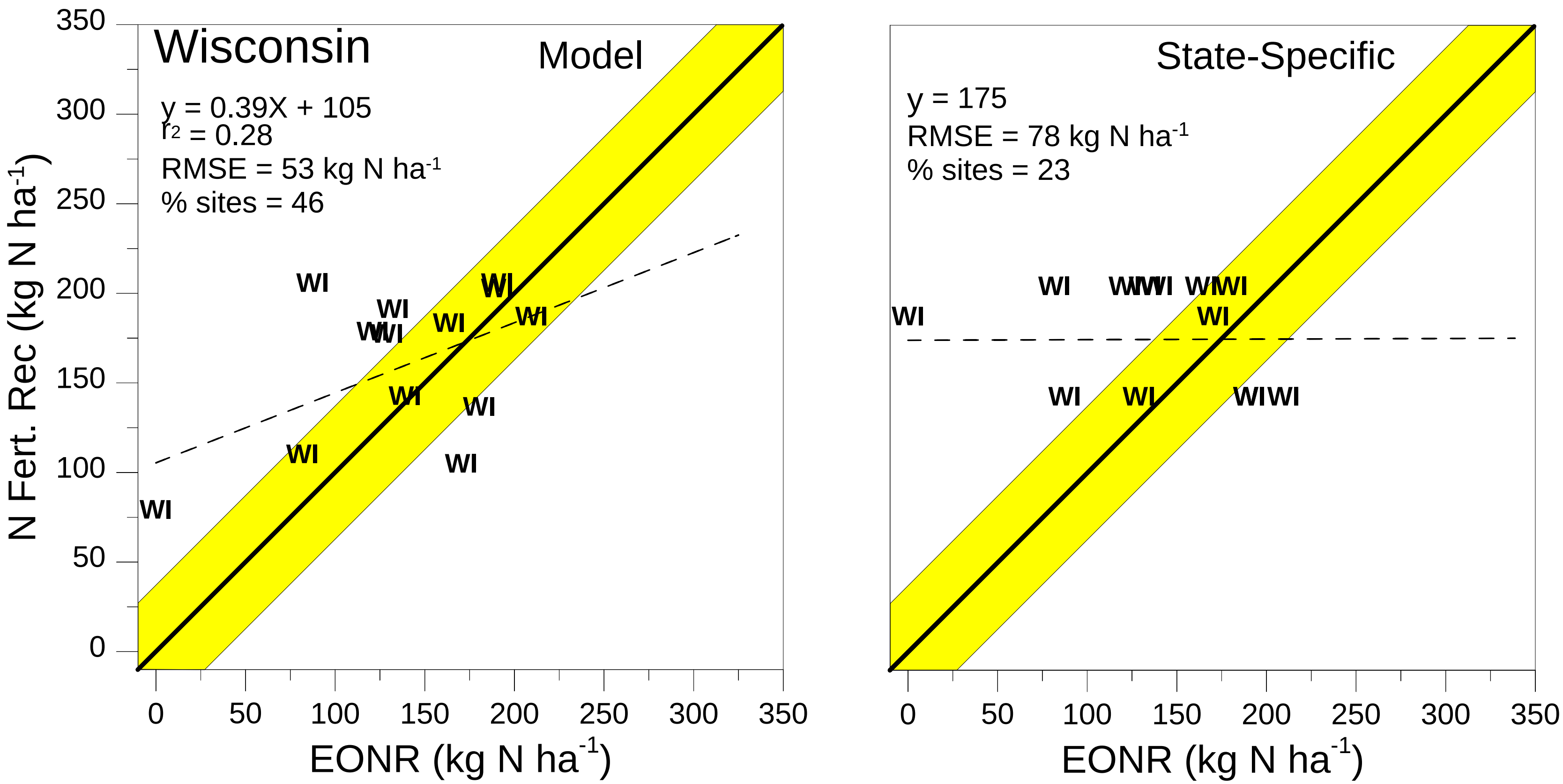

Figure 4.9. The hydrologic soil group (HG) based model N fertilizer recommendations for WI compared to the WI-specific Maximum Return to Nitrogen (MRTN) tool. For non-significant relationships between the model recommendation and EONR the slope was set to zero and no r^2 reported. Site-years that fall within the yellow band are within 34 kg N ha^{-1} of EONR. Overall, the HG-based model outperformed the WI-specific MRTN tool for estimating EONR.

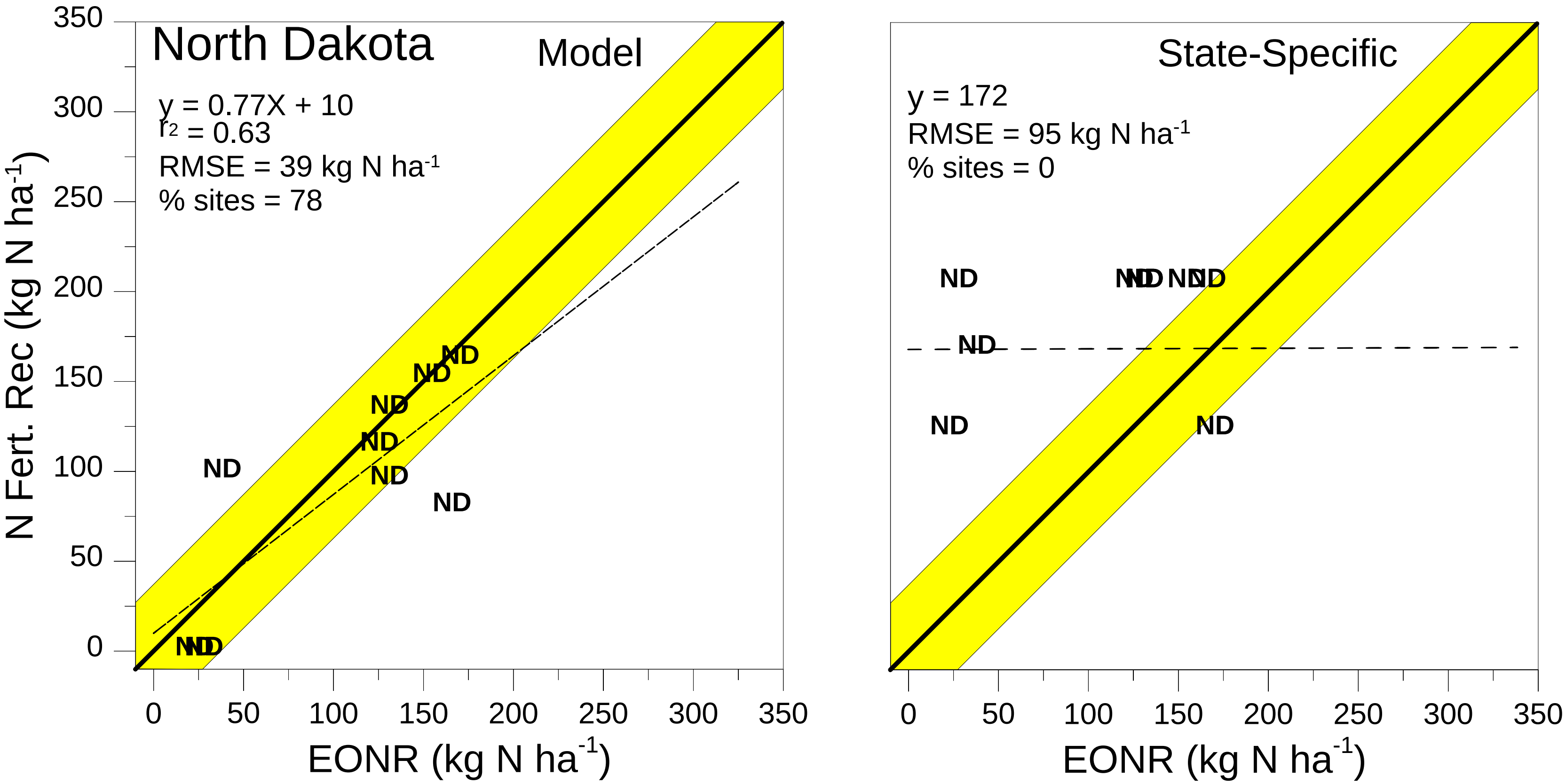

Figure 4.10. The hydrologic soil group (HG) based model N fertilizer recommendations for ND compared to the ND-specific Maximum Return to Nitrogen (MRTN) tool. For non-significant relationships between the model recommendation and EONR the slope was set to zero and no r^2 reported. Site-years that fall within the yellow band are within 34 kg N ha^{-1} of EONR. Overall, the HG-based model outperformed the ND-specific MRTN tool for estimating EONR.

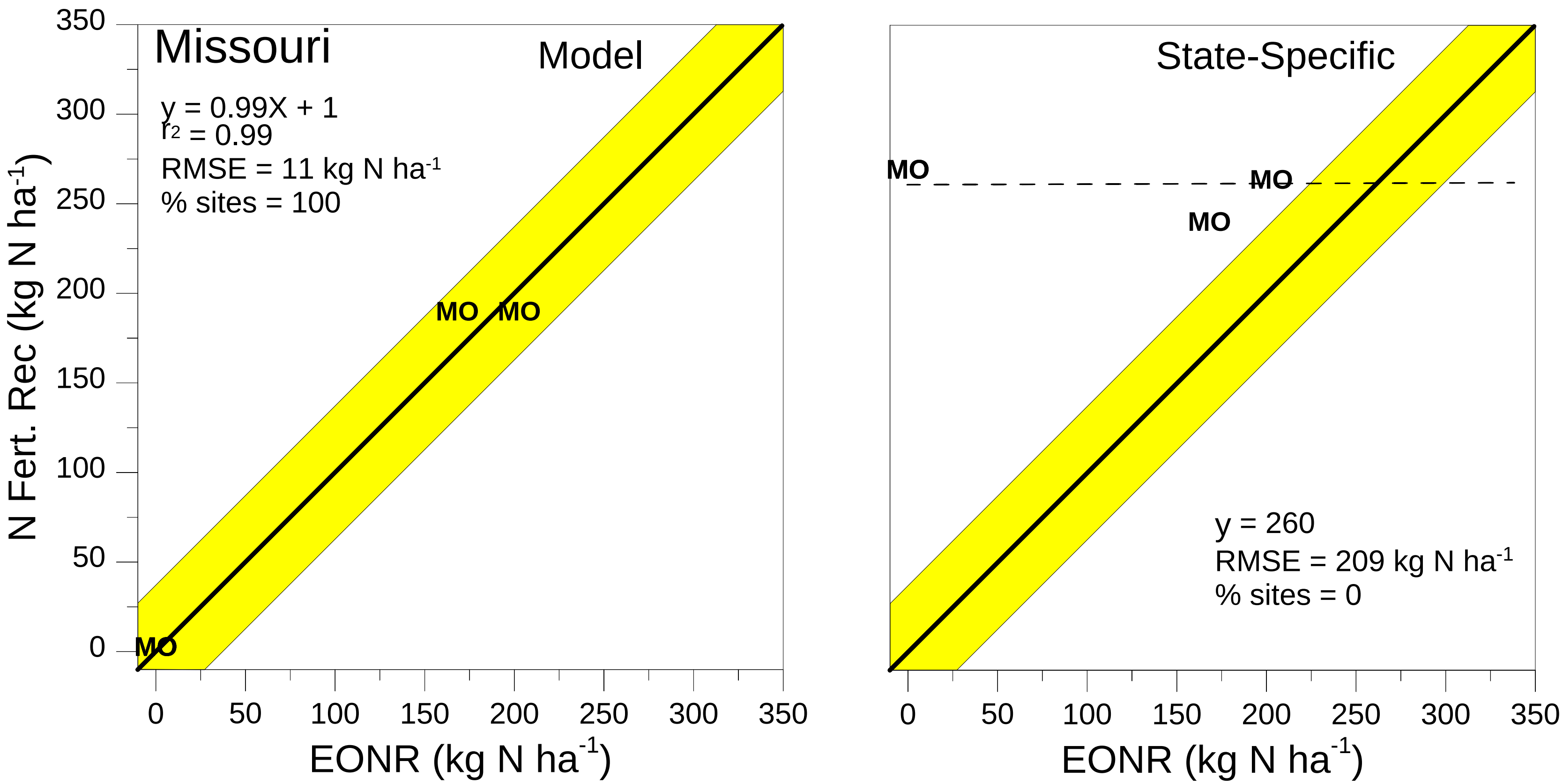

Figure 4.11. The hydrologic soil group (HG) based model N fertilizer recommendations for MO compared to the MO-specific yield goal calculation. For non-significant relationships between the model recommendation and EONR the slope was set to zero and no r^2 reported. Site-years that fall within the yellow band are within 34 kg N ha^{-1} of EONR. Overall, the HG-based model outperformed the MO-specific yield goal calculation for estimating EONR.

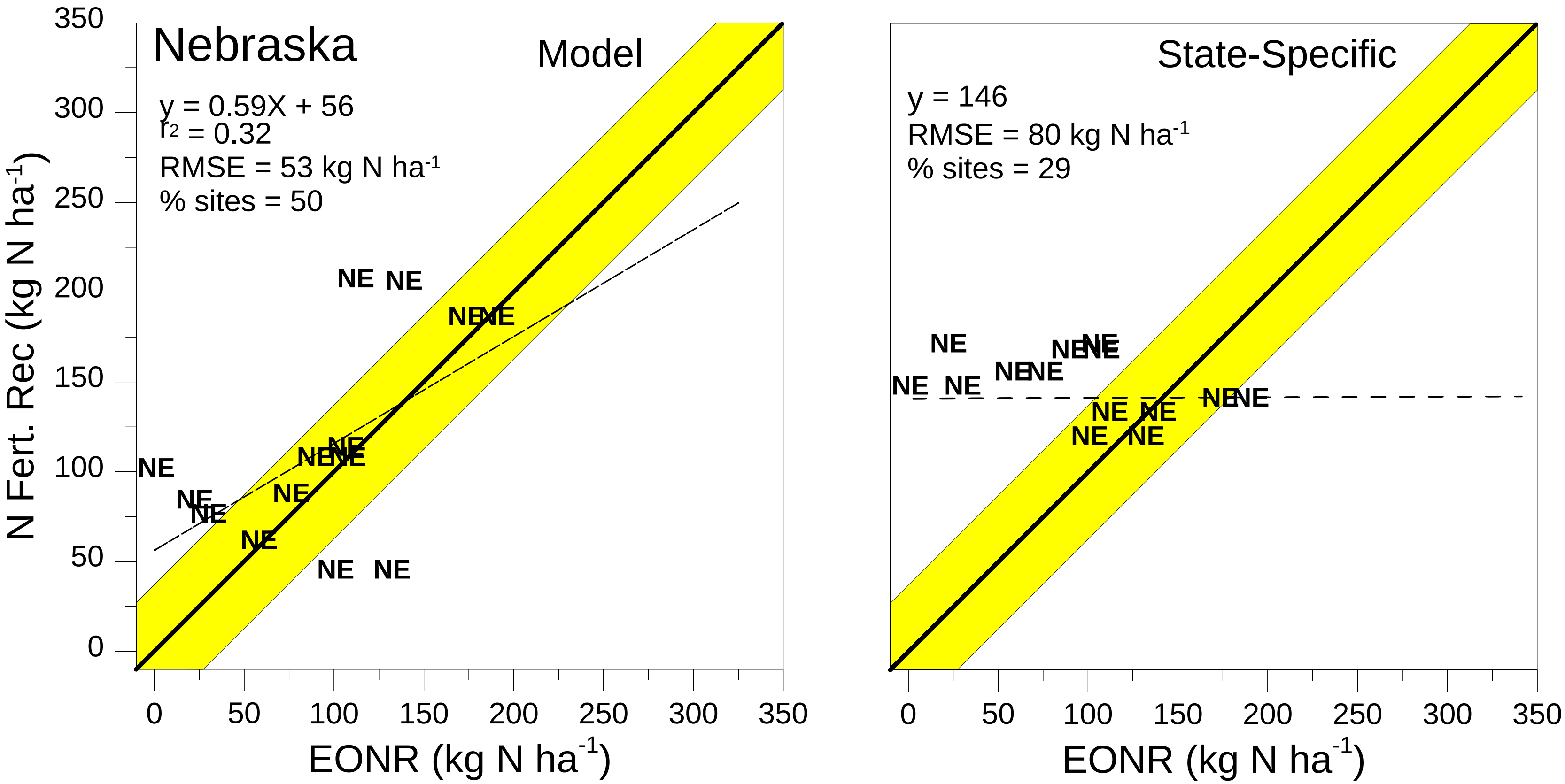

Figure 4.12. The hydrologic soil group (HG) based model N fertilizer recommendations for NE compared to the NE-specific yield goal calculation. For non-significant relationships between the model recommendation and EONR the slope was set to zero and no r^2 reported. Site-years that fall within the yellow band are within 34 kg N ha^{-1} of EONR. Overall, the HG-based model outperformed the NE-specific yield goal calculation for estimating EONR.

Dissertation Conclusion

Efforts to maximize corn (*Zea mays* L.) yield often result in over-applying N fertilizer, consequently leading to financial loss and environmental contamination. Matching N fertilizer application rates with corn N need can decrease the likelihood of N loss. However, predicting corn N need is difficult due to spatial and temporal variability. Therefore, the aim of this dissertation was to develop and evaluate empirically-derived N fertilizer recommendation models capable of accounting for soil and weather characteristics. Using a regional U.S. Midwest Corn Belt dataset (totaling 49 sites over three growing seasons), models were created by using linear regression analysis to determine which soil and/or weather factors best related to the economic optimal N rate (EONR) within delineated groups based on USDA-NRCS soil classification. The created models were then evaluated using compiled outside datasets from six U.S. Midwest states. Several important observations were made during model creation and evaluation. These include: 1) soil and weather information most significantly related to EONR varied by N application time, 2) this model approach outperformed current state-specific N recommendation tools, and 3) using USDA-NRCS soil classification allowed for a better prediction of the fate of N for alike soils and therefore improved N recommendations. These results suggest further research should be performed to validate the applicability and usefulness of this approach.

VITA

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