2017

# A Public–Industry Partnership for Enhancing Corn Nitrogen Research and Datasets: Project Description, Methodology, and Outcomes

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**Abstract**

Due to economic and environmental consequences of N lost from fertilizer applications in corn (*Zea mays* L.), considerable public and industry attention has been devoted to the development of N decision tools. Needed are research and databases and associated metadata, at numerous locations and years to represent a wide geographic range of soil and weather scenarios, for evaluating tool performance. The goals of this research were to conduct standardized corn N rate response field studies to evaluate the performance of multiple public-domain N decision tools across diverse soils and environmental conditions, develop and publish new agronomic science for improved crop N management, and train new scientists. The geographic scope, scale, and unique collaborative arrangement warrant documenting details of this research. The objectives of this paper are to describe how the research was undertaken, reasons for the methods, and the project's anticipated value. The project was initiated in a partnership between eight U.S. Midwest land-grant universities, USDA-ARS, and DuPont Pioneer. Research using a standardized protocol was conducted over the 2014 through 2016 growing seasons, yielding a total of 49 sites. Preliminary observations of soil and crop variables measured from each site revealed a magnitude of differences in soil properties (e.g., texture and organic matter) as well as differences in agronomic and economic responses to applied N. The project has generated a valuable dataset across a wide array of weather and soils that allows investigators to perform robust evaluation of N use in corn and N decision tools.

**Disciplines**

Agricultural Economics | Agricultural Science | Agronomy and Crop Sciences | Environmental Sciences | Soil Science

**Comments**

This article is published as Kitchen, N. R., J. F. Shanahan, C. J. Ransom, C. J. Bandura, G. M. Bean, J. J. Camberato, P. R. Carter, J. D. Clark, R. B. Ferguson, F. G. Fernández, D. W. Franzen, 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.

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## ABSTRACT

Due to economic and environmental consequences of N lost from fertilizer applications in corn (*Zea mays* L.), considerable public and industry attention has been devoted to the development of N decision tools. Needed are research and databases and associated metadata, at numerous locations and years to represent a wide geographic range of soil and weather scenarios, for evaluating tool performance. The goals of this research were to conduct standardized corn N rate response field studies to evaluate the performance of multiple public-domain N decision tools across diverse soils and environmental conditions, develop and publish new agronomic science for improved crop N management, and train new scientists. The geographic scope, scale, and unique collaborative arrangement warrant documenting details of this research. The objectives of this paper are to describe how the research was undertaken, reasons for the methods, and the project's anticipated value. The project was initiated in a partnership between eight U.S. Midwest land-grant universities, USDA-ARS, and DuPont Pioneer. Research using a standardized protocol was conducted over the 2014 through 2016 growing seasons, yielding a total of 49 sites. Preliminary observations of soil and crop variables measured from each site revealed a magnitude of differences in soil properties (e.g., texture and organic matter) as well as differences in agronomic and economic responses to applied N. The project has generated a valuable dataset across a wide array of weather and soils that allows investigators to perform robust evaluation of N use in corn and N decision tools.

## Core Ideas

- The geographic scope, scale, and unique collaborative arrangement warrant documenting details of this work.
- The purpose of this article is to describe how the research was undertaken, reasons for the research methods, and the project's potential value.
- The project generated a valuable dataset across a wide array of weather and soils that allows evaluation of N decision tools.

Published in Agron. J. 109:2371–2388 (2017)
doi:10.2134/agronj2017.04.0207
Available freely online through the author-supported open access option

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FEEDBACK from grower surveys often lists N fertilizer management among the more challenging aspects of modern corn production. This is because soil N availability and plant uptake varies dynamically as a result of the complex interactions between the crop, soil, and weather (Tremblay et al., 2012). Consequently, the economic optimum nitrogen rate (EONR) to apply for a given field can differ substantially from year to year (Sawyer and Nafziger, 2005; Nafziger et al., 2008), and within fields due to spatial variability in soil properties (Mamo et al., 2003; Scharf et al., 2005; Shahandeh et al., 2005; Shanahan et al., 2008). For these reasons, growers can inadvertently under- or over-apply N, reducing profitability (Lambert et al., 2006). In cases where N is over-applied, the potential risk for environmental degradation increases (Jaynes et al., 2001; Shanahan et al., 2008; Shcherbak et al., 2014).

Due to the economic and environmental consequences of N lost from the plant root zone, there has been a considerable amount of public and private research effort devoted to the development of decision tools for determining optimal N rate. Thus, there are a wide variety of tools available to growers for estimating the corn N need for specific fields and even subregions of fields (Morris et al., 2017). These include the mass balance approach based on a yield goal or yield potential (not currently recommended in the majority

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**Abbreviations:** EONR, economic optimal nitrogen rate; G×E×M, genetics × environment × management; MRMS, multi-radar/multi-sensor; MRTN, maximum return to nitrogen; PPNT, pre-plant soil nitrate test; PSNT, pre-side-dress soil nitrate test; YEONR, yield at the economic optimum nitrogen rate.

of the U.S. Midwest Corn Belt region), pre-plant soil nitrate test (PPNT), pre-side-dress soil nitrate test (PSNT), maximum return to nitrogen (MRTN), crop growth models, and in-season N applications using active-optical reflectance sensors. Morris et al. (2017) provides a summary of the development and the strengths and weaknesses of many corn N recommendation tools. Despite the extensive research effort devoted to the development of these tools and their evaluation, there have been few investigations conducted to compare their performance in the same study and under the wide array of soils and climate that represent the U.S. Corn Belt. One recent regional study was conducted to compare crop modeling (Maize-N) vs. active crop canopy sensing approaches for recommending in-season N fertilizer rates (Thompson et al., 2015). While this work provided useful insights regarding the relative performance of these two approaches, the results have limited application to the entire Corn Belt region (only three U.S. states were involved). Additionally, the experimental design for that research did not include the necessary N treatments to calculate a precise optimal N rate, so tool performance evaluation was limited. In another study, a wide range of soil and weather environments may have been explored, but only one N management decision tool was evaluated (Scharf et al., 2006).

Because of the lack of side-by-side research comparing N decision tools, and the opportunity to study N response in corn across a wide geographic region, a regional multi-year, public-industry research project was conducted. Specific research findings from this project will follow in coming years. The purpose of this paper is to document how the research project was undertaken, provide the research methods, and describe the project's potential value. This narrative will provide details that can aid in future studies of similar focus and the necessary descriptions for meta-analysis when the raw data is made publically available. The specific objectives of this paper are:

1. Describe: (i) process and procedures of the project development; (ii) multi-state scale for diversity in soil and weather environments; (iii) public-industry partnership, agreements, and organizational structure; (iv) standardized materials and methods; (v) data organization and certification; (vi) graduate student research questions, education, and publication; and (vii) project resource management.
2. Summarize: (i) descriptive statistics results; (ii) timeline and anticipated science outcomes; and (iii) project advantages and value.

## PROJECT DESCRIPTION

### Process and Procedures of Project Development

The overall approach for the project involved a fundamental N fertilizer rate response field-plot study including a single at planting application and split applications, conducted with standardized methods across a wide array of soil and weather conditions of the U.S. Corn Belt. The investigation of this project was conducted in the following eight states: Illinois, Indiana, Iowa, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin. Yield, soil, plant, and weather measurements were collected at each study site to provide N response functions that were used to evaluate each of the decision tools. In this manner, the N rate that would have been recommended by a specific tool could be referenced with the EONR determined from the response function, providing a quantitative assessment of tool performance. Additionally, the ancillary soil, plant, and weather data can be used to better understand corn N response and develop new agronomic science for improved crop N management. Although this research was conducted in the U.S. Midwest, the methodology and research outcomes will be applicable to agronomic studies across larger regions throughout the world.

### Multi-State Scale for Diversity in Soil and Weather Environments

Since a goal of this research was to evaluate N decision tools for their ability to prescribe optimal N rates across a wide array of conditions represented by the U.S. Corn Belt, a multi-state investigation was deemed essential to accomplishing that goal. That approach was supported by research findings from Tremblay et al. (2012), who conducted an extensive study covering 51 diverse locations in North America over a 4-yr period. They found that soil properties and weather conditions had profound effects on corn yield response to applied N. Therefore, for this project investigators from each of eight states were asked to select two contrasting sites for each of the three study years (2014 through 2016); one located on a highly productive soil and the other on a relatively less productive soil. New sites were identified each year. This produced 49 total research sites (Missouri conducted the study at 3 sites in 2016) over the 3 yr (Fig. 1a and Table 1). The locations encompassed a major portion of the Corn Belt region (Fig. 1b) and represented a wide range of soil (Fig. 1a and Fig. 2) and climatic conditions (Fig. 1c and 1c). The sites were well distributed across the three major soil orders (Alfisol, Mollisols, and Entisols) found in the region, with the more poorly drained sites (Alfisol soils) found primarily in southern Illinois and central Missouri. A few sites were located on Entisols near a major river. Average annual rainfall varies substantially across the region, increasing by almost twofold from the northwest to the southeast. Rainfall distribution for the region varies seasonally, with 70 to 80% of the precipitation concentrated in the spring and summer of the growing season (April–October). Average annual temperatures also vary widely across the region, increasing from the north to the south. Because average temperatures vary dramatically, the growing season length also ranges widely across the region. For example, the average length of growing season (defined as frost-free days from planting to physiological maturity) available to bring corn to maturity ranges from only around 90 d in the far northern portion of the study up to nearly 120 d in the southern portion (data not shown). Longer-season hybrids typically possess higher yield potential. To accommodate these differences in growing season length across the research sites, DuPont Pioneer brand hybrids were selected with suitable comparative relative maturity ratings and other desirable traits to maximize yield potential while minimizing risk to frost injury for a given site. The hybrids (Table 1) used in this study ranged in comparative relative maturity rating from 89 to 115 d.

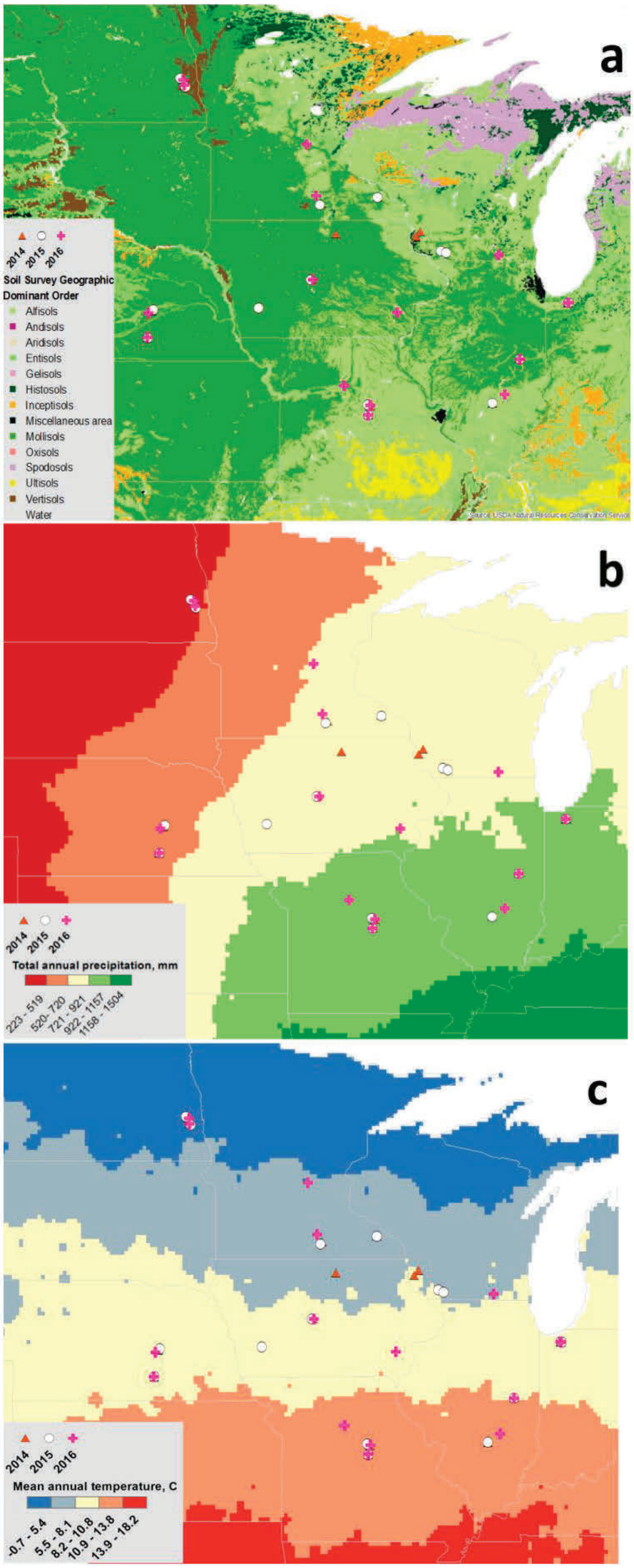
### Public-Industry Partnership, Agreements, and Organizational Structure

Due to the challenges in executing a project of this scale and scope, it was thought that a collaboration involving university researchers located in states across the U.S. Corn Belt was essential for success. Hence, the project was undertaken as a public-industry partnership between DuPont Pioneer and researchers at eight land-grant universities to represent the eight states previously identified (University of Illinois, Purdue University [Indiana], Iowa State University, University of Minnesota, University of Missouri and USDA-ARS, University of Nebraska-Lincoln, North Dakota State University, and University of Wisconsin-Madison). A critical component of a public/private partnership is that all partners receive something of value. The primary interests of the university investigators were to evaluate public-domain N decision tools, develop new agronomic science for improved crop N management, train new scientists, and contribute to scientific knowledge by publishing research results.

The key interests of DuPont Pioneer, the industry partner in this project, were to produce a dataset for validation and improvement of their new N decision tool, and to facilitate the training of new scientists. In addition to being a provider of hybrid seed, DuPont Pioneer also provides agronomic management suggestions to customers, assisting them in making the greatest possible profit from their seed products. DuPont Pioneer recently launched the Encirca Services platform, which is marketed to growers as a means for more efficient and sustainable management of crop inputs including genotype, seeding rate, and crop nutrients (N, P, K). The Encirca N service is a cloud-based decision tool that uses models in combination with site-specific soil and weather information obtained from customer farms, to deliver site-specific N applications (Heggenstaller and Munaro, 2016). For their part on the project, DuPont Pioneer provided seed of various hybrids, financial support for graduate students and research scientists, financial support for research costs, in-kind contributions of equipment (weather stations, soil moisture probes, and active-optical sensors), soil and plant analysis services, aerial images, and the assembly and management of weather data collected from weather stations at each study site. This totaled approximately US$2 million over the 3 yr of the project. There was an additional contribution of both University and DuPont Pioneer research and other staff time that was approximately similar in amount.

To formalize this partnership, DuPont Pioneer legal personnel worked with legal representatives from each of the eight land-grant Universities to execute contractual agreements. The project was led by Dr. Newell Kitchen (USDA-ARS Soil Scientist and an adjunct faculty member at the University of Missouri), with the university principal investigators from the other states serving as the overall project team leadership. The five graduate students funded by the project performed much of the work in four states, with research scientists and technicians primarily helping to conduct the research for the other four states. Members of the Agronomy Sciences team from DuPont Pioneer also served in an advisory capacity to the project. The principal investigation team, as well as graduate students, met monthly via teleconference calls and annually in face-to-face meetings, to discuss research progress, interpret results, coordinate graduate student research, clarify or modify protocols, and develop publication plans.

Rules for what constitutes authorship vary between institutions, organizations, professional societies, and scientists (Osborne and Holland, 2009). After reviewing policies of reputable journals and the organizations represented by the principal investigators, a publication policy statement was accepted. It stated that all authors on any project publications are expected to contribute to all phases of a publication, including:



Source: USDA Natural Resources Conservation Service

Fig. 1. Maps of study region depicting spatial distribution of (a) USDA-NRCS great soil orders, (b) mean annual rainfall from NOAA, and (c) mean annual temperature. The locations of the 49 study sites from 2014 to 2016 are shown within the eight states Iowa, Illinois, Indiana, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin. Some sites from 1 yr to the next were in close proximity and may be hidden by later-year symbols.

Table 1. Soil and management characteristics of all sites.

| Year | State | Site | Soil Survey Geographic Database (SURRGO) Soil Series | Previous crop† | Tile drained | Irrigated | Tillage‡ | Hybrid§ |
|---|---|---|---|---|---|---|---|---|
| 2014 | IA | Ames | Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludolls) | Soybean | No | No | SSF | P0987AMX |
|  | IA | MasonCity | Readlyn (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) | Soybean | Yes | No | No-till | P0636AMX |
|  | IL | Brownstown | Cisne (fine, smectitic, mesic Mollic Albaqualfs) | Soybean | No | No | SSF | P1498AM |
|  | IL | Urbana | Flanagan (fine, smectitic, mesic Aquic Argiudolls) | Soybean | No | No | SSF | P1498AM |
|  | IN | Loam | Sebewa (fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiaquolls) | Soybean | No | No | FC/SSF | P0987AMX |
|  | IN | Sand | Tracy (coarse-loamy, mixed, active, mesic Ultic Hapludalfs) | Soybean | No | No | FC/SSF | P0987AMX |
|  | MN | New Richland | Webster/Canisteo– Glencoe (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) | Soybean | Yes | No | No-till | P9917AMX |
|  | MN | St. Charles | Seaton (fine-silty, mixed, superactive, mesic Typic Hapludalfs) | Soybean | No | No | SSF | P9917AMX |
|  | MO | Bay | Mexico (fine, smectitic, mesic Vertic Epiaqualfs) | Soybean | No | No | SD/SSF | P1498AM |
|  | MO | Troth | Lowmo (coarse-silty, mixed, superactive, mesic Fluventic Hapludolls) | Soybean | No | No | No-till | P1498AM |
|  | ND | Amenia | Glyndon–Tiffany (coarse-silty, mixed, superactive, frigid Aeric Calciaquolls) | Corn | No | No | FC/SSF | P8954AM1 |
|  | ND | Durbin | Fargo (fine, smectitic, frigid Typic Epiaquerts) | Corn | Yes | No | FC/SSF | P8954AM1 |
|  | NE | Brandes | Libory (sandy over loamy, mixed, mesic Oxyaquic Haplustolls) | Soybean | No | Yes | No-till | P1151HR |
|  | NE | SCAL | Crete (fine, smectitic, mesic Pachic Udertic Argiustolls) | Soybean | No | Yes | No-till | P1151HR |
|  | WI | Steuben | Huntsville (fFine-silty, mixed, superactive, mesic Cumulic Hapludolls) | Soybean | No | No | No-till | P0636AMX |
|  | WI | Wauzeka | Pepin (fine-silty, mixed, superactive, mesic Typic Hapludalfs) | Soybean | No | No | No-till | P0636AMX |
| 2015 | IA | Boone | Clarion/Webster (fine-loamy, mixed, superactive, mesic Typic Hapludolls) | Soybean | No | No | SSF | P0987AMX |
|  | IA | Lewis | Marshall (fine-silty, mixed, superactive, mesic Typic Hapludolls) | Soybean | No | No | No-Till | P1498AM |
|  | IL | Brownstown | Cisne (fine, smectitic, mesic Mollic Albaqualfs) | Soybean | No | No | SSF | P1498AM |
|  | IL | Urbana | Flanagan (fine, smectitic, mesic Aquic Argiudolls) | Soybean | Unknown | No | SSF | P0987AMX |
|  | IN | Loam | Sebewa (fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiaquolls) | Soybean | No | No | FC/SSF | P0987AMX |
|  | IN | Sand | Tracy (coarse-loamy, mixed, active, mesic Ultic Hapludalfs) | Soybean | No | No | FC/SSF | P0987AMX |
|  | MN | New Richland | Webster/Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) | Soybean | Yes | No | FC/SSF | P0157AMX |
|  | MN | St. Charles | Seaton (fine-silty, mixed, superactive, mesic Typic Hapludalfs) | Soybean | No | No | SSF | P0157AMX |
|  | MO | Lone Tree | Mexico (fine, smectitic, mesic Vertic Epiaqualfs) | Soybean | No | No | SD/SSF | P1498AM |
|  | MO | Troth | Lowmo (fine-silty, mixed, superactive, mesic Fluvaquentic Hapludolls) | Soybean | No | No | SSF | P1498AM |
|  | ND | Amenia | Lankin (coarse-loamy, mixed, superactive, frigid Pachic Hapludolls) | Corn | No | No | FC/SSF | P9188AMX |
|  | ND | Durbin | Fargo (fine, smectitic, frigid Typic Epiaquerts) | Corn | Yes | No | FC/SSF | P9188AMX |
|  | NE | Brandes | Ipage (mixed, mesic Oxyaquic Ustipsamments) | Soybean | No | Yes | No-till | P1151HR |
|  | NE | SCAL | Crete (fine, smectitic, mesic Pachic Udertic Argiustolls) | Soybean | No | Yes | No-till | P1151HR |
|  | WI | Belmont | Tama (fine-silty, mixed, superactive, mesic Typic Argiudolls) | Soybean | No | No | No-till | P0987AMX |
|  | WI | Darlington | Dodgeville (fine-silty over clayey, mixed, superactive, mesic Typic Argiudolls) | Soybean | No | No | No-till | P0987AMX |

Continued next page.

Table 1. (continued).

| Year | State | Site | Soil Survey Geographic Database (SURRGO) Soil Series | Previous crop† | Tile drained | Irrigated | Tillage‡ | Hybrid§ |
|---|---|---|---|---|---|---|---|---|
| 2016 | IA | Crawford | Mahaska (fine, smectitic, mesic Aquertic Argiudolls) | Soybean | Yes | No | SSF | P1197AMXT |
|  | IA | Story | Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) | Soybean | Yes | No | SSF | P1197AMXT |
|  | IL | Shumway | Cisne (fine, smectitic, mesic Mollic Albaqualfs) | Soybean | No | No | SSF | P1197AM |
|  | IL | Urbana | Flanagan (Fine, smectitic, mesic Aquic Argiudolls) | Soybean | Unknown | No | SSF | P1197AMXT |
|  | IN | Loam | Sebewa (fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiaquolls) | Soybean | No | No | SSF | P1197AMXT |
|  | IN | Sand | Tracy (coarse-loamy, mixed, active, mesic Ultic Hapludalfs) | Soybean | No | No | FC/SSF | P1197AMXT |
|  | MN | Becker | Hubbard–Mosford (sandy, mixed, frigid Entic Hapludolls) | Soybean | No | Yes | SD/SSF | P0157AMX |
|  | MN | Waseca | Cordova (fine-loamy, mixed, superactive, mesic Typic Argiaquolls) | Soybean | No | No | FC/SSF | P0157AMX |
|  | MO | Bradford | Mexico (fine, smectitic, mesic Vertic Epiaqualfs) | Soybean | No | No | SD/SSF | P1197AM |
|  | MO | Loess | Higginsville (fine-silty, mixed, superactive, mesic Aquic Argiudolls) | Soybean | No | No | SSF | P1197AM |
|  | MO | Troth | Peers (fine-silty, mixed, superactive, mesic Fluvaquentic Hapludolls) | Soybean | No | Yes | SD/SSF | P1197AM |
|  | ND | Amenia | Glyndon (coarse-silty, mixed, superactive, frigid Aeric Calciaquolls) | Soybean | No | No | FC/SSF | P9188AMX |
|  | ND | Durbin | Hegne (fine, smectitic, frigid Typic Epiaquerts) | Sunflower | Yes | No | FC/SSF | P9188AMX |
|  | NE | Kyes | Lockton (fine-loamy over sandy or sandy-skeletal, mixed, mesic Cumulic Haplustolls) | Soybean | No | Yes | No-till | P1197AMT |
|  | NE | SCAL | Hastings (fine, smectitic, mesic Udic Argiustolls) | Corn | No | Yes | No-till | P1197AMT |
|  | WI | Lorenzo | Lorenzo (fine-loamy over sandy or sandy-skeletal, mixed, active, mesic Typic Argiudolls) | Soybean | No | No | No-till | P0157AMX |
|  | WI | Plano | Plano (fine-silty, mixed, superactive, mesic Typic Argiudolls) | Soybean | No | No | No-till | P0157AMX |

† Soybean [*Glycine max* (L.) Merr.]; sunflower (*Helianthus annuus* L.).

‡, FC, fall chisel; SD, spring disk; SSF, spring soil finisher.

§ More information on DuPont Pioneer brand corn hybrids can be found at https://www.pioneer.com/home/site/us/products/corn/seed-guide/.

(i) conception and execution or analysis and interpretation; (ii) drafting the article or revising it for critically important intellectual content; and (iii) final approval of the version to be published. Multi-state level publications would include the lead principal investigator from the states contributing data. Other potential co-authors that meet the three criteria for authorship stated above could include graduate students, DuPont Pioneer investigators, and other state-level investigators or support scientists.

## STANDARDIZED MATERIALS AND METHODS

A key element of the project was standardization of research procedures to minimize uncontrolled error, thereby improving the ability to interpret the impact of the range of environmental conditions on corn response to N fertilization. This standardization was in part a necessity driven by the tremendous geographic extent of the research (1.35 million km$^2$ represented by the eight U.S. states involved) and the involvement of a team of more than 20 individuals conducting field trials. Therefore, one of the first responsibilities of the principal investigators was to develop a standardized set of methods for field research implementation, crop and soil measurements, data collection, data quality analysis, and finally data certification. Following generally accepted procedures documented in the scientific literature, methods were drafted, discussed, and refined into a protocol document. Protocol details also included describing project organization, coordination and communication, roles of all investigators, site selection criteria, site characterization, experimental design, N fertilization treatments and implementation, use of common equipment, sample schedule, sample labeling, soil and plant sampling procedures, sample processing, sample storage, data management, and publication review and authorship. The protocol document was kept as a single source, shared through Box Inc. (Redwood City, CA) and modified when clarification details warranted. (Box is a secure cloud file service the universities associated with this project approved and supported because of its rigid security standards.) During monthly project teleconference meetings, specific protocol instructions were reviewed prior to implementation. Also, the written protocol was supplemented by private YouTube videos, produced specifically for the project, to visually demonstrate equipment installation or operational details (such as active-optical sensor operations and soil moisture apparatus installations).

To help with standardization of the soil characterizations, a single research crew originating from Missouri traveled to each trial site prior to spring planting and sampled the soil profile (four 1.2-m depth cores per site), described and sampled soil by pedogenic horizon, and processed samples for laboratory analysis. On the same day, an apparent soil electrical conductivity (EC$_a$) survey was obtained at each site using a Veris Technologies V3100 electrical conductivity detector (Veris Technologies, Salina, KS). The EC$_a$ data were collected on transects

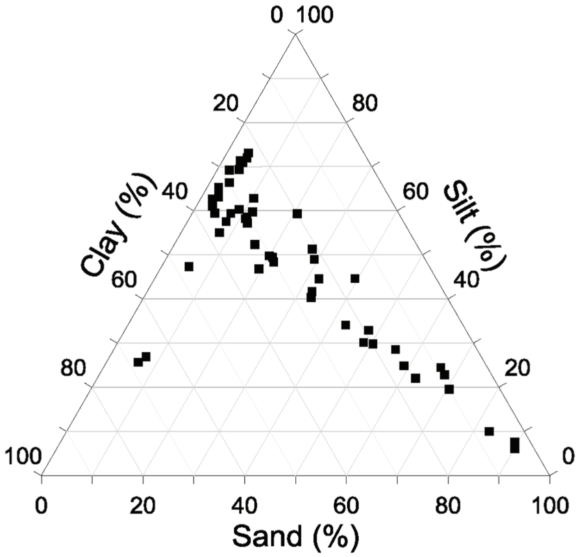


Fig. 2. Profile (1.2-m depth) average sand, silt, and clay content for the 49 research sites.

approximately 5 m apart on 1 s intervals, with the instrument pulled through the experimental plot areas at approximately 2 m s$^{-1}$, which corresponded to a measurement about every 2 m along the transects. All $EC_a$ measurements were georeferenced using DGPS receivers. Other $EC_a$ collection details have been previously published (Sudduth et al., 2003, 2005).

While most reputable labs that provide soil and plant analysis services are accredited by independent testing and certification entities to establish proficiency, the principal investigators agreed to use a single lab that employed accepted QA/QC protocols for specific analyses to remove potential lab-to-lab variation. Soil samples from the site characterization were analyzed for soil physical and chemical properties by the University of Missouri Soil Health Assessment Center. This lab has been in operation over 30 yr (under different names) and regularly performs analyses on samples from across North America. Plant N and soil nitrate N analyses were completed by Agvise Laboratories located in Northwood, ND. A subset of samples was also analyzed for ammonium N (University of Missouri Soil Testing Laboratory) and N mineralization tests (USDA-ARS Cropping Systems and Water Quality Research Unit- Soil Microbiology Laboratory located in Columbia, MO).

To ensure that standardized procedures were used for collection of weather information, DuPont Pioneer assumed a central leadership role. Weather data for each growing season were obtained with HOBO (model U30) weather stations (Onset Corporation, Bourne, MA) located at each site. Raw and summarized data (maximum and minimum temperatures, solar radiation, and total precipitation) were uploaded daily to a DuPont Pioneer cloud server via cellular connection for centralized data archiving, management, and quality assessment. The summarized daily data were quality checked against interpolated temperature data from Multi-Radar/Multi-Sensor (MRMS) rainfall data (The National Severe Storms Lab, NOAA). Any outliers and/or missing values were identified and replaced by the interpolated temperature or MRMS rainfall estimates. Daily global solar radiation was estimated using Bristow–Campbell equation (Bristow and Campbell, 1984) with parameters optimized based on ground observational data collected from 239 weather stations across U.S. contiguous states during 1961 to 1990 (Renewable Resources Data Center, Golden, CO).

Sixteen N fertilizer treatments with four replications were used in a randomized complete block design at each site. Eight treatments consisted of all N fertilizer applied at planting (0–315 kg N ha$^{-1}$ on 45 kg ha$^{-1}$ increments). Six treatments constituted a split application, with a low N fertilizer rate at planting (45 kg N ha$^{-1}$) plus side-dress (V9 ± one corn development stage as described by Abendroth et al., 2011) rates (45–270 kg N ha$^{-1}$ on 45 kg ha$^{-1}$ increments). Two additional split treatments were medium N at planting (90 kg N ha$^{-1}$) plus two side-dress rates (90 and 180 kg N ha$^{-1}$) (treatments are summarized in Table 2). A single source of ammonium nitrate was used for all sites each year (provided by El Dorado Chemical Company, Rockwell, TX). Ammonium nitrate was used because we expected it to perform more similarly across the range of environmental conditions represented by the study region, to be independent of N recommendation tools being evaluated, to provide for uniform broadcast application, to allow for soil nitrate and ammonium N assessment shortly after fertilizer application, and be acceptable for surface application.

A summary of baseline site characterization, in-season soil, plant, and weather measurements, and management and historical records collected is provided in Table 3. Additional descriptive details of the materials and methods included in the project protocol document are provided in Table 4, and a timeline of sampling is provided in Table 2. Other specific methods, data calculations, and statistical analyses will be documented when detailed research findings are published.

## Data Organization and Certification

Microsoft Excel (Microsoft Corp, Redmond, WA) spreadsheets were developed as templates for organizing and storing data. Files for each data type (e.g., soil nitrate N, soil characterization, plant, and yield) were prepared for each state at the beginning of each year. This helped to communicate the necessary data to be collected. Datasheets included variable names standardized across the different data types. The templates included embedded formula calculations (e.g., plot yields transformed into conventional units). The first sheet of each spreadsheet was a “variable description” sheet, with each variable name with the variable units, variable description (including formula calculations when applicable), and relevant scientific citations.

Each principal investigator was responsible for certifying raw data they collected. Certification meant the results were examined for being reasonable based on the type of measurements, comparability to prior like-studies with similar treatments, N treatments of the study, and similarity across replications. For soil nitrate N and plant N results, a project level “outlier report” was generated using box and whisker plots and the Cook’s distance metric to visualize potential outliers. Based on these examinations, a few soil and plant samples (<1% of more than 30,000 samples) were reanalyzed. Different results were found for about 15% of rerun samples. Principal investigators were given authority to designate especially questionable data as missing values, but were encouraged only to do so when the questionable data corresponded to issues noted with field observations or aerial images.

In addition to certification of raw data, the team agreed to standardize the process of developing and testing the yield response functions and calculation of EONR (corn grain price, $ 0.158 kg$^{-1}$

Table 2. Nitrogen application treatments and soil and plant sampling timeline. Within the table, X indicates sampling occurred at all sites and the O indicates supplemental samples collected at sites in 2015 (IA [1], IL [2], MO [2], NE [2]) and 2016 (IA [1], IL [2], MO [1], and NE [2]).

| Treatment | N Fertilizer rates | | | Soil nitrate-N sampling schedule | | | | | Plant N sampling schedule | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| no. | Planting | Side-dress | Total | V5 | V9 | VT | R4† | Post-harvest | V5 | V9 | VT | R4† | R6 |
| | kg N ha$^{-1}$ | | | | | | | | | | | | |
| 1 | 0 | 0 | 0 | X | O | X | O | X | O | O | X | O | X |
| 2 | 45 | 0 | 45 | X | O | O | O | X | O | O | X | O | X |
| 3 | 90 | 0 | 90 | X | O | X | O | X | O | O | X | O | X |
| 4 | 135 | 0 | 135 | X | O | O | O | X | O | O | X | O | X |
| 5 | 180 | 0 | 180 | X | O | X | O | X | O | O | X | O | X |
| 6 | 225 | 0 | 225 | X | O | O | O | X | O | O | X | O | X |
| 7 | 270 | 0 | 270 | X | O | X | O | X | O | O | X | O | X |
| 8 | 315 | 0 | 315 | X | O | O | O | X | O | O | X | O | X |
| 9 | 45 | 45 | 90 | | | X | | X | | | X | | X |
| 10 | 45 | 90 | 135 | | | | | X | | | X | | X |
| 11 | 45 | 135 | 180 | | | X | | X | | | X | | X |
| 12 | 45 | 180 | 225 | | | | | X | | | X | | X |
| 13 | 45 | 225 | 270 | | | X | | X | | | X | | X |
| 14 | 45 | 270 | 315 | | | | | X | | | X | | X |
| 15 | 90 | 90 | 180 | | | X | | X | | | X | | X |
| 16 | 90 | 180 | 270 | | | | | X | | | X | | X |

† For supplementary samples in 2015 only.

[\$4.00 bu$^{-1}$]) and N fertilizer cost (\$0.88 kg N$^{-1}$ [\$0.40 lb$^{-1}$]) to ensure consistency in the anticipated research publications. Over past decades there have been several different modeling options explored for fitting model's yield response data (Cerrato and Blackmer, 1990; Scharf et al., 2005; Sawyer et al., 2006). Often the quadratic-plateau (Q-P) model is identified as the most appropriate model for corn N response. In addition to the Q-P model, the quadratic (Q), linear-plateau (L-P), and linear models were also examined. Models were determined for each of the two N fertilizer application times associated with the treatments of this study: all N applied at planting and split with 45 kg N ha$^{-1}$ at planting with the majority of N applied at side-dress. Performance of the Q-P model was almost always best using the metrics of significance of model probability, coefficient of determination ($R^2$), and root mean square error (RMSE). In only a few cases did the L-P or Q models marginally improve compared to the Q-P model (e.g., $R^2$ increase of ≤0.03), therefore, the Q-P model was accepted for all but one of these research sites. At this one site, the Q model was accepted because it had a greater $R^2$ and lower RMSE than Q-P model. Sites were identified as non-responsive to N when the Q-P model probability was insignificant ($P > 0.10$). This was the case for 6 out of the total 98 response functions, and for those cases the EONR was set at 0 kg N ha$^{-1}$. A few sites never reached the plateau, were best described with a linear model, and for these sites, EONR was set at the maximum N rate of 315 kg N ha$^{-1}$.

Upon certification, the data were compiled across all sites and years into single spreadsheets by data type and filed into the Box (Box, Redwood City, CA) cloud storage.

## Research Questions, Graduate Education, and Publication

An overall objective of this research was to obtain soil and plant measurements over a range of environments that allowed for both economic and indirect environmental evaluation of corn N response and decision tools. Additionally, the data were expected to be used to modify or develop new tools for recommending N. Primary response functions of interest included EONR, agronomic efficiency, fertilizer N use efficiency, residual soil nitrate N, and potential N loss. Each of these may be examined within each site, collectively across subsets of sites, or across all sites.

Graduate student education and training has been a major emphasis for the principal investigators. The concept of giving graduate students an opportunity to contribute to and then draw on a dataset that spanned over eight U.S. states was considered unique and valuable. In some instances, graduate students traveled beyond their own states and assisted in other states, which gave them a greater understanding of the diversity in soils and growing environments represented by the project. Each of the graduate students and their adviser identified objectives they wished to address, and then as a project team these objectives were discussed and approved. A shared document outlining the objectives was kept for reference, which provided a helpful communication tool regarding graduate student research emphasis. The document included the investigator and graduate student name, investigation title, objectives or hypotheses, data type to be used and from what states, and the team approval date. A summary of working objectives is found in Table 5.

## Project Resource Management

Execution of multi-institutional projects can be challenging because of procedural differences among the organizations. For this project, DuPont Pioneer worked one-on-one with each of the individual universities to produce agreements with common language that ensured standardization and promoted efficiency. Funding was conditional on the requirement to follow the methods and procedures outlined in the protocol document. Much of the equipment for soil and plant measurements (e.g., soil water sensors and data loggers, weather stations, canopy reflectance sensors) as well as most laboratory measurements (e.g., soil N, plant N, baseline characterization) were paid directly by DuPont Pioneer, minimizing overhead accounting costs.

Table 3. Measurements, methods, and associated citations for this project.

| Parameter | Method | References and methods |
|---|---|---|
| Site characterization | | |
| Soil properties by pedological horizon | | |
| Texture | Pipette | Soil Survey Staff (2014) 3A1 |
| Cation exchange capacity | Ammonium acetate | Soil Survey Staff (2014) 4B1a1a1a1a-b1 |
| Total C | Dry combustion | Soil Survey Staff (2014) 4H2a1 |
| Total inorganic C | Difference between total carbon and organic portion of C | |
| Total organic C | Dry combustion | Nelson and Sommers (1996) |
| Organic matter | Loss-on-ignition | Soil Survey Staff (2014) 5A |
| pH | pH meter (salt and water) | Soil Survey Staff (2014) 4C1a1a and 4C1a1a2 |
| Bulk density | Core | Soil Survey Staff (2014) 3B6a |
| Electrical conductivity | 1:1 paste | Rhoades (1982) |
| Profile soil | | |
| Apparent soil electrical conductivity | Veris 3100 | Sudduth et al. (2005) |
| Soil fertility | | |
| pH | pH Meter | Thomas (1996) |
| Phosphorus | Colorimetry (Bray I, Mehlich III, or Olson P) | Kuo (1996) |
| Potassium | Colorimetry (ammonium acetate, Bray I, or Mehlich III) | Helmke and Sparks (1996) |
| Organic matter | Loss-on-ignition | Nelson and Sommers (1996) |
| Sampling and measurements | | |
| Soil | | |
| Nitrate-N | Colorimetry | Gelderman and Beegle (1998), Mulvaney (1996) |
| Ammonium N | Colorimetry | Keeney and Nelson (1982) |
| Mineralization | Anaerobic incubation | Bundy and Meisinger (1994), Keeney and Bremner (1966), Rhine et al. (1998) |
| Soil moisture | Electrical resistance | Eldredge et al. (1993) |
| Tissue | | |
| Grain N | Dry combustion | Bremner (1996) |
| Tissue N | Dry combustion | Bremner (1996) |
| N uptake | Calculations based on biomass and N concentrations | Sawyer et al. (2017) |
| Crop color and biomass | | |
| Canopy reflectance sensor | Hand held RapidSCAN CS-45 | Holland and Schepers (2010), Kitchen et al. (2010), Shanahan et al. (2008) |
| Aerial images | VIS and NIR | Sripada et al. (2006), Zhang and Kovacs (2012) |
| Harvest | | |
| Yield | Hand or combined harvested | |
| Management and historical records | | |
| Current and past cropping system history and management | Survey from land manager or researcher | |
| Weather | | |
| Photosynthetically active radiation | Measures wavelengths from 400 to 700 nm | Daily average using HOBO weather stations instrumentation (Onset Computer Corporation, Bourne, MA). Proprietary DuPont Pioneer weather interpolation methods for days where weather was not recorded before and after growing season or due to sensor maintenance issues. |
| Temperature/ relative humidity | Senor with solar radiation guard | |
| Precipitation | Tipping bucket | |

Table 4. Standardized protocol details for site, weather, soil, and plant parameters.

| Measurements | Protocol |
|---|---|
| Research site selection | • Two sites were selected each year from each state based on contrasting soil productivity.<br>• Sites were either on a producer's field or on a public agricultural research station.<br>• Corn was grown following soybean, corn, or sunflower for 43, 5, and 1 of the 49 site, respectively.<br>• Individual principal investigators (PI) decided if new sites were to remain on the same farm or if different farms were to be chosen. No previous sites were used a second time. |
| Management and historical records | All management records were recorded for the current-year research:<br>• Dates of research and management practices (e.g., soil and plant sampling, fertilizer applications, herbicide applications, and tillage).<br>• Irrigation events.<br>• Nitrate-N content of irrigation water.<br>• Herbicide applications.<br>• Other observations (e.g., weather, disease, insect populations, nutrient deficiencies, etc).<br>• Target corn seeding rate.<br>• Corn row spacing.<br>• Routine soil fertility test results, 0- to 15-cm depth composite sample per replicate from the study area.<br>• Fertilizers used if called for by soil testing or known need.<br>• Percent residue on the surface of soil.<br>• Expected yield reported by farmer or PI.<br>• Expected yield calculated using a 5-yr county yield average and adjusted based on the yield potential of the soil. This soil yield potential was determined using the "Nutrient Application Guidelines for Field, Vegetable, and Fruit Crops in Wisconsin" extension publication (Laboski et al., 2012). County average yield was increased by 30, 20, and 10% based on the yield potentials of "High", "Medium", and "Low", respectively.<br>Previous 5-yr of management records:<br>• Crop rotation schedule.<br>• Previous N fertilizer rates.<br>• Manure applications.<br>Site description:<br>• GPS location of the study site.<br>• Tiled drained.<br>• Estimated grade of slope.<br>• SSURGO soil series. |

Continued next page

Table 4 (continued).

| Measurements | Protocol |
|---|---|
| Profile apparent soil electrical conductivity ($EC_a$) and coordinates of plot boundaries | Each site was surveyed using the same Veris 3100 instrument (Veris Technologies, Inc., Salina, KS) in the spring one to four weeks prior to planting. Three sites were resurveyed the following spring as a result of high measurement error.<br>• Data was obtained by running approximately 4.6 m spaced transects at 1.3 m $s^{-1}$ resulting in about one sample recorded every second.<br>• An additional four to six transects were done perpendicular at 9-m spacing intervals to the original passes.<br>• All $EC_a$ measurements were georeferenced using DGPS receivers.<br>• A minimum of 800 total observations per site were recorded.<br>• Both a shallow and a deep reading were obtained at each sampling point.<br>• All observations were cleaned by deleting erroneous points that were associated with poor coulter-to-soil contact—often a result of turning or uneven soil associated with no-till or ridge-till practices.<br>After the corn was harvested, plot boundaries were recorded with either DGPS or RTK—when available.<br>• A minimum of 45 points were taken at the outside edge of all the plots and on the corners of plots within the site to be able to interpolate the boundaries of each plot.<br>• Corners of each plot were digitized after fitting a grid to the DGPS or RTK points that matched the plot dimensions using Surfer 12.8 (Golden Software, LLC, Golden, CO).<br>Plot specific data of $EC_a$ was determined by:<br>• Creating an interpolated map for shallow and deep reading using kriging with local variograms in ArcGIS 10.1 (ESRI, Redlands, CA, USA).<br>• The plot boundaries were spatially joined with the interpolated $EC_a$ shallow and deep maps.<br>• Site $EC_a$ data was summarized by each individual plot to obtain a plot average, minimum, maximum, and standard deviation of both shallow and deep $EC_a$ readings. |
| Site characterization:<br>*Soil organic and inorganic carbon (TOC and TIC), total carbon (TC), total nitrogen (TN), pH, cation exchange capacity (CEC), particle size (soil texture), organic matter (OM), paste EC, and bulk density (BD)* | Site $EC_a$ maps were created to identify soil variability to determine where soil characterization samples were to be taken:<br>• Data was mapped by separating data into 10 equal categories based on the range of data.<br>• Four cores, one from each block at the time of the ECa survey, were collected to capture the range of spatial soil variability within the field.<br>• Using the previously flagged areas where the blocks were to be positioned, the $EC_a$ map of the site was used to identify areas where cores were to be taken that would capture the range of spatial soil variability.<br>• Cores were taken using a hydraulic sampler (Giddings Machine Company Inc., Windsor, CO) to a depth of 1.2 m using a 5.1-cm diam. tube with a 3.8- to 4.- cm diam. bit.<br>• Cores were described by horizon and the depth of each horizon recorded.<br>• Each horizon was split and placed in plastic sample bags. Samples were chilled with ice in coolers until transported to the University of Missouri for processing.<br>• Samples were air dried, ground using a mortar and pestle, and passed through a 2 mm sieve.<br>• Samples were submitted to the University of Missouri's Soil Health Assessment Center for soil physical and chemical analysis:<br>* TOC, TC, and TIC: Dry combustion of ~0.5 g using a LECO C-144 Carbon Determinator (LECO Corporation, Saint Joseph, MI, USA). The temperature initiates at room temperature and slowly increases to 927°C. TOC is determined by an early peak whereas TC is determined by additional loss up to 927°C. TIC is the difference between TC and TOC.<br>* TN: Dry combustion using a LECO FP-F528 Nitrogen/Protein Determinator (LECO Corporation, Saint Joseph, MI).<br>* pH: 1:1 soil/water pH and 1:1 soil/salt (1 M KCl) pH.<br>* CEC: Ammonium acetate buffered to pH 7.00 and steam distilled.<br>* Texture: Pipette analysis after removing organic matter.<br>* OM: Loss-On-Ignition using Thermogravimetric Analyzer (LECO Corporation, Saint Joseph, MI).<br>Four soil cores taken to duplicate the site characterization cores were split by horizon in the same increments and used to calculate BD and gravimetric water content. Samples were weighed before and after oven drying at 105°C until constant dry weights were obtained. Bulk density was calculated as the dry weight of soil divided by the volume of soil, determined by the length of the horizon and the surface area of the bit used to pull the core. |
| Routine soil fertility | Each state took a 0- to 15-cm composite soil sample from the research area (or each replicate) up to four weeks prior to planting. Samples were processed and submitted to a laboratory used by each state for routine soil fertility analysis. Nutrient and pH deficiencies were corrected prior to planting to maintain soil tests at optimal fertility levels for corn production. |
| Corn hybrids and seeding rate | Sites were planted with DuPont Pioneer brand hybrids as determined appropriate for each site based on growing degree days and previous insect and disease occurrences. The target planting population was 86,500 seeds $ha^{-1}$. Adjustments were made based on local practices according to soil productivity. The average viable population was 80,700 plants $ha^{-1}$ across all site-years. |

Continued next page

Table 4 (continued).

| Measurements | Protocol |
|---|---|
| Plot dimensions | Plot sizes varied by state but ranged from 12.2 to 18.2 m long by 3.05 to 9.1 m wide. The width of the planting rows was 0.762 m for all states except North Dakota which used 0.559 m. Plots were long enough where grain yield could be determined from a minimum area of 18.5 $m^2$. |
| Nitrogen treatments | Nitrogen fertilizer was applied to the soil surface as ammonium nitrate (El Dorado Chemical Co. Rockwell, TX).<br>A common spreadsheet was used with embedded formulas to calculate fertilizer amounts. Fertilizer was applied at two different times, either all at planting (within 7 d of the time of planting, however, some sites applied fertilizer as early as 29 d prior to planting) or a split application at planting with an in-season application applied at V9 +/–1 growth stage. North Dakota sites for 2015 and 2016 applied the in-season N application between V5 and V8.<br>Treatments were set up in a randomized complete block design with four blocks of 16 N rate treatments (Table 2). |
| Corn canopy reflectance sensing | Corn canopy reflectance measurements were taken using a RapidSCAN CS-45 Handheld Crop Sensor (Holland Scientific, Lincoln, NE) with wavelengths at 670, 730, and 780 nm. The two 2014 North Dakota sites used a CC-430 (Holland Scientific, Lincoln, NE) with the same wavelengths as the RapidSCAN CS-45.<br>• Calibrated sensors using manufacturer's guidelines.<br>• Measurements were collected at V9 +/– 1 growth stage just prior to in-season N applications, except for 2015 and 2016 North Dakota sites where sensing took place between V5 and V8.<br>• The sensor was held 30 cm above the crop canopy, using a metal rod attachment as a reference.<br>• Data was taken from the two middle harvest rows of each plot, walking approximately 4 km $h^{-1}$.<br>• The mean of 200 to 300 readings was used to represent each plot. |
| Aerial imagery | Photographs were taken from either a fixed-wing aircraft or an unmanned aerial vehicle (UAV) depending on the weather and availability of pilots. When possible, both visible (440–675 nm) and near infrared (710–830 nm) were obtained. In some instances, only the visible wavelengths were measured.<br>Target corn growth stages for aerial images:<br>2014: VT–R2 using a fixed-wing airplane with a mounted multispectral camera (Cornerstone Mapping Inc., Lincoln, NE) at a resolution of 25 cm. Images were obtained from Iowa, Indiana, Illinois, Minnesota, Missouri, Nebraska, and Wisconsin sites.<br>2015: V4–V6, V8–V10, VT–R2, and R4 using a fixed wing airplane mounted with 12bit CCD camera at a spatial resolution of 25 cm (GeoVantage, Inc., Buffalo, NY). Images were obtained from Iowa, Illinois, Indiana, Minnesota, and Nebraska sites. The Iowa site was also flown with a UAV mounted with a multispectral camera (PrecisionHawk, Raleigh, NC).<br>2016: V8–10 and VT–R2 using a fixed wing airplane with a mounted 12bit CCD camera (GeoVantage, Inc., Buffalo, NY, USA) for Iowa, Illinois, and Indiana sites. Other sites were flown with a UAV mounted with a multispectral camera (PrecisionHawk, Raleigh, NC, USA) for Iowa, Illinois, Missouri, and Nebraska sites. Thermal imagery was captured at Minnesota, Nebraska, and Wisconsin sites between the VT–R2 growth stage using a fixed-wing airplane with a mounted thermal infrared camera (7.5–14 µm wavelength; Cornerstone Mapping Inc., Lincoln, NE, USA). Imagery for North Dakota sites were obtained between the VT–R2 growth stage using a UAV mounted with a multispectral camera using red edge narrow bands (670, 700, and 730 nm) and RGB color (Sentera Quad; Sentera, LLC, Minneapolis, MN, USA). |
| Soil nitrate-N | Sample timing, depth, treatments, and quantity of samples taken:<br>Pre-plant (PPNT): Ten cores were taken with a hand-probe and combined to represent each block to a depth of 90 cm, separated in 30-cm increments.<br>Pre-side-dress (PSNT): Six cores were taken with a hand-probe from Treatments 1 through 8 (Table 2) and combined to represent each plot to a depth of 60 cm, separated in 30-cm increments.<br>Tasseling (VT): Three cores were taken with a hand-probe from odd numbered treatments (Table 2) and combined to represent each plot to a depth of 60 cm, separated in 30-cm increments.<br>Post-harvest: Sampling occurred within 1 to 4 wk after harvest. Three cores, using a 4.13-cm diam. core and 3.0 cm diameter tip, were taken from each plot with a hydraulic sampler (Giddings Machine Company Inc., Windsor, CO). The three cores, taken from the harvest rows, were separated into 30-cm increments and combined to represent each plot.<br>Supplemental samples: Additional samples were taken from select treatments for a subset of the participating states (Table 2).<br>Sample handling and analysis procedures:<br>Samples were air or oven dried (≤ 32°C) depending on the state within 12 h of sampling. If samples were unable to be air dried they were frozen or refrigerated until samples could be processed. Dried samples were crushed with a flail-type grinder, passed through a 2-mm sieve, and homogenized before sending to Agvise Laboratories (Northwood, ND) for soil nitrate-N analysis. A 7.65 g soil sample was mixed with 19.13 mL of 0.2 M KCl, shaken for >5 min, filtered and soil nitrate-N determined using the Cadmium Reduction method (Gelderman and Beegle, 1998) with a modified Technicon AutoAnalyzer (SEAL Analytical, Inc., Fareham, UK). |

Continued next page

Table 4 (continued).

| Measurements | Protocol |
|---|---|
| Soil ammonium | Ammonium-N was measured on a subset of soil samples taken for nitrate-N determination at University of Missouri's Soil and Plant Testing Laboratory. The surface 0- to 30-cm soil samples from each of the following sampling timings and treatments were analyzed:<br>PPNT: Topsoil from each of the four blocks<br>PSNT: (0-0, 90-0, 180-0, and 270-0 kg N ha$^{-1}$ treatments) from each of the four blocks<br>VT: (0-0, 90-0, 180-0, 270-0, 45-135, and 90-90 kg N ha$^{-1}$ treatments) from each of the four blocks<br>Procedure:<br>• Ten grams of dried and ground soil sample was added with 25 mL 2 M KCl and shaken for 5 min on a reciprocating shaker. The solution was filtered and the extractant analyzed for ammonium-N using the ammonia phenolate method with a Lachat Flow Injection Analyzer (Lachat Instruments, 1997; QuickChem Method 12-107-06-1-B; Hatch Company, Loveland, CO). |
| Potentially mineralizable nitrogen | Potentially mineralizable N was determined on a subset of soil samples taken for nitrate-N analysis. Samples returned from Agvise Laboratories were submitted to the USDA-ARS Soil Microbiology Laboratory for analysis. The surface 0- to 30-cm soil samples from the pre-plant (PPNT) and the V5 [(PSNT) 0-0 and 180-0 kg N ha$^{-1}$ treatments] soil sampling timings were used for the anaerobic potentially mineralizable N test.<br>Procedure:<br>• Twenty milliliters of ultrapure water was added to 4 g of soil in 50 ml Falcon tubes (Corning Inc., Corning, NY) and incubated for 7-, 14-, and 28-d at 40°C (Keeney and Bremner, 1966).<br>• After the incubation, 20 mL of 4 M KCl was added and samples were shaken for 30 min.<br>• The solution was passed through a washed 0.45 µm syringe filter disk and stored in a microtube at –80°C until ammonium-N analysis could be done.<br>• Ammonium-N produced was determined by the Berthelot method (Rhine et al., 1998) using a Glomax Multidetection System plate reader (Promega Biosystems, Inc., Sunnyvale, CA).<br>• An initial ammonium-N value was determined for each treatment and subtracted from the incubated samples to calculate net ammonium-N (Bundy and Meisinger, 1994). |
| Plant aboveground biomass and N content. | Sample timing and treatments:<br>VT: Six plants were taken from a representative area within each plot that would not be used for grain yield estimation. The six-plant sample was cut at ground level and processed as a whole plant. All treatments from all experimental units (64 plots) were sampled.<br>R6: Six plants were taken from within the harvest rows at the onset of physiological maturity determined by the start of black layer. Grain and cobs were first separated from above ground biomass before processing. All treatments from all blocks were sampled.<br>Supplemental samples: Additional plants were sampled (six) from select treatments from a subset of the participating states (Table 2). In 2015, supplemental plant samples were taken at V5, V9, and R4 growth stages. In 2016, supplemental plant samples were taken at V5 and V9. The V5 samples were taken on the border rows of each plot. While the V9 samples were taken from the middle two rows of each plot, with three plants taken from first 1.5 m of each side of the plot. The R4 samples were taken within the harvest area and all above ground biomass processed together, including the cobs and grain. Grain yield in the plots with R4 samples was adjusted for the collected plants.<br>Procedure:<br>• Wet weights of all six plants were taken shortly after cutting the plant.<br>• Plants were then either dried as whole samples or chipped and subsampled before drying at 60 to 70°C. At R6, ears were removed before chopping the wet vegetative material, with a subsample collected for moisture determination.<br>• Dry weights were obtained after samples reached a constant weight.<br>• Plants were then ground and passed through a <1 mm sieve and shipped to Agvise Laboratories. Dry weights of cob and grain were obtained after drying at 60 to 70°C.<br>• Grain was ground and sent to Agivse Laboratories.<br>• Total N in plant tissue and grain was determined using the Dumas Combustion method with an Elementary Rapid N Cube Nitrogen Analyzer (Elementar Analysensyteme GmbH, Langenselbold, Germany).<br>Nitrogen in plants before physiological maturity:<br>Vegetative N (and vegetative plus grain and cob for R4 samples) content:<br>$VN = V_{dry} \times NC_V$<br>Where $V_{dry}$ was the dry matter of the six plant samples (converted to an area basis by plant population) and $NC_v$ the plant material total N concentration, dry matter based. Units kg ha$^{-1}$.<br>Nitrogen in plants at maturity:<br>Six-plant vegetative moisture:<br>$V_{moist}$ = (vegetative wet subsample weight – dry subsample weight)/(wet subsample weight)<br>Where the moisture was determined from a subsample of chopped plant vegetative material. Units %. |

Continued next page

Table 4 (continued).

| Measurements | Protocol |
|---|---|
| | Six-plant field moisture weight:<br>VF = wet vegetative weight of six plants<br>Where the vegetative weight of the six plants was determined before chopping. Units g. |
| | Six-plant grain weight:<br>GR6 = dry grain weight of the six plants<br>Where the six-plant grain dry weight was measured. Units g. |
| | Six-plant cob weight:<br>C6 = dry cob weight of the six plants<br>Where the six-plant cob dry weight was measured. Units g. |
| | Six-plant vegetative weight:<br>$V6 = (1 - V_{moist}) \times VF$<br>Where the six-plant vegetative wet weight was converted to dry matter basis. Units g. |
| | Cob harvest index:<br>CHI = GR6/(C6+GR6)<br>Where the cob harvest index was based on the six-plant sample. |
| | Grain harvest index:<br>HI = GR6/(GR6+V6+C6)<br>Where the grain harvest index was based on the six-plant sample. |
| | Grain yield:<br>GY= harvested plot weight plus six plant grain weight<br>Where the total plot grain harvest was converted to dry matter weight per area basis (yield). Units kg $ha^{-1}$. |
| | Cob dry matter yield:<br>CY = (GY/CHI)-GY<br>Where the cob dry matter was converted to a weight per area basis (yield) by using the harvested plot grain yield (GY). Units kg $ha^{-1}$. |
| | Vegetative yield:<br>VY = (GY/HI)-GY-CY<br>Where the vegetative dry matter (yield) was calculated from the grain harvest index and grain yield (GY), with subtraction of grain yield and cob yield (CY). Units kg $ha^{-1}$. |
| | Grain N content:<br>$GN = GY \times NC_g$<br>Where the grain N content, area based, was calculated by multiplying the grain dry matter yield times the grain N concentration ($NC_g$). Units kg $ha^{-1}$. |
| | Vegetative N content:<br>$VN = VY \times NC_v$<br>Where the vegetative N content, area based, was calculated by multiplying the vegetative dry matter yield times the vegetative N concentration ($NC_v$). Units kg $ha^{-1}$. |
| | Cob N content:<br>$CN = (GN+VN) \times 0.048$<br>Where the cob N content, area basis, was estimated by a conversion factor (48 +/–13 g $kg^{-1}$ of total N uptake) times the grain N (GN) plus the vegetative N (VN); as the cob was not analyzed for N concentration. Units kg $ha^{-1}$. |
| | Total plant N content:<br>TN = GN+VN+CN<br>Where the total aboveground plant N content, area basis, was determined by adding the grain N (GN), vegetative N (VN) and cob N (CN). Units kg $ha^{-1}$. |

Continued next page

Table 4 (continued).

| Measurements | Protocol |
|---|---|
| Weather | Hobo U30 automatic weather stations (Onset Computer Corporation, Bourne, MA) were set up adjacent to each trial site. Each weather station was equipped with sensors attached to a data logger to measure:<br>• Precipitation collected using a tipping bucket.<br>• Photosynthetically active radiation sensor (400–700 nm).<br>• Temperature and relative humidity, with a solar radiation guard.<br>Procedure:<br>• Sensors were connected to a telemetric data logger (TX300; Onset Computer Corporation, Bourne, MA) and readings recorded every 15 min.<br>• Sensors were monitored throughout the season and rain gauges cleaned of debris when observed.<br>• The 2014 North Dakota Amenia site used an NDAWN (North Dakota Agricultural Weather Network) weather station which was located 5.6 km from the site.<br>• The 2016 Missouri Bradford site did not have a weather station and used weather gathered from the University of Missouri's Bradford research station, a distance of 1.9 km from the site.<br>Historic climate data was propagated for each site from the previous 30 yr. |
| Soil moisture | Four plots per site had moisture probes (Watermark 200SS; The Irrometer Company, Inc., Riverside, CA) placed at depths of 30, 60, 90, and 120 cm.<br>• The four sensors were placed in two N treatments of 90 kg N ha$^{-1}$ applied all at planting and 270 kg N ha$^{-1}$ split application with 90 kg N ha$^{-1}$ applied all at planting and 180 kg N ha$^{-1}$ applied at side-dress.<br>• Sensors were connected to a Watermark Monitor 900M data logger (The Irrometer Company, Inc., Riverside, CA) taking readings every 6 h.<br>• Sensors were installed in the middle of the harvest row between emerging corn plants. The sensors were attached to PVC tubing to allow for easy installation and removal.<br>The measured electrical resistance was converted to a volumetric soil water content using the conversion factors developed by Saxton and Rawls (2006). The texture and organic matter obtained from the site characterization samples were used as inputs for this equation.<br>One additional soil moisture sensor (TriSCAN Sensor; Sentek Sensor Technologies, Stepney, SA, Australia) was installed at each site in 2015.<br>• The sensor was installed adjacent to the Watermark sensors in the plot receiving 280 kg N ha$^{-1}$ split applied.<br>• The sensor was installed to a depth of 120 cm shortly after corn emergence.<br>• Readings were taken every 15 min at 5-cm depth increments. |
| Economic optimal nitrogen rate (EONR) and N response models | A quadratic-plateau, linear-plateau, quadratic, or linear model was fit to grain yields as a function of N fertilizer rate. A yield response model was fit separately for each N application timing at a site. The model for at plant N application included Treatments 1 through 8 (Table 2) while the one for split applications included Treatments 1, 2, and 9 through 14 (Table 2).<br>• At six of sites and timings, none of the evaluated models was significant ($P < 0.10$), meaning there was no yield response to increasing N rate.<br>• For all but one timing at one site, the quadratic-plateau model was used based on improved $R^2$ and lower RMSE values compared to the linear-plateau.<br>• The 2016 Wisconsin Plano site for all N applied at planting, a quadratic model had a greater $R^2$ and lower RMSE values compared to the other models.<br>• At four sites and timing, yield did not plateau and a linear model was fit to the data.<br>An EONR value for each site was calculated using a corn price of US\$0.157 kg$^{-1}$ and an N fertilizer price of \$0.88 kg$^{-1}$. The EONR for non-responsive sites was set at 0 kg ha$^{-1}$. For linear models, EONR was set at the maximum N rate applied of 315 kg N ha$^{-1}$. |

## PROJECT SUMMARY

### Descriptive Statistic Results

The research included 49 sites over three growing seasons (2014–2016) spanning eight U.S. Corn Belt region states. Intensive analysis of the dataset with hypothesis testing will follow in subsequent publications. Here we provide a summary of general data (only descriptive statistical analysis), to provide the reader a sense of the variable soils, weather, and N responses encompassed across the sites. The research was conducted on a wide range of soils represented by different soil textures (Fig. 2). Based on average 1.2-m profile measurements, most sites would be classified as silty clay loam, silt loam, or loam soil textures. Nine sites were either sand, loamy sand, or sandy loam. Three sites were silty clay or clay. Likewise, soil organic matter and total N were highly variable across the sites (Fig. 3).

Averaged across all sites, the EONR averaged 169 and 159 kg N ha$^{-1}$ for fertilizer applied at planting and split-applied (side-dress ~V9), respectively, but ranged between 0 and 315 kg N ha$^{-1}$ across both application timings (Fig. 4). This wide range in EONR illustrates the difficulty associated with generating accurate N fertilizer guidelines for diverse soil, weather, and previous crop management conditions. Average yield response to N, yield at economic optimal nitrogen rate (YEONR), and EONR agronomic efficiency at the EONR were all slightly greater with split N application versus all N applied at planting (Fig. 4). In summary, the descriptive statistics for the key soil and crop variables presented here confirm and satisfy two desired requirements for a successful outcome to the project: (i) there was indeed considerable difference in soil properties across the 49 sites, and (ii) the inherent soil and climatic differences combined with the standardized N treatment protocol at each site allowed measurements of large differences in corn response (YEONR and EONR) to applied N across the diverse environments. Hence, this project has generated valuable data over a wide array of weather and soil environments that will allow a robust evaluation of the performance of N decision tools as well as answer other questions regarding N fertilizer management.

### Timeline and Anticipated Science Outcomes

The project has or will have three distinctive but overlapping phases: phase 1, field implementation and data collection; phase 2, graduate student analyses and publication, and phase 3, enhanced analyses and publication. The first phase is completed, having been initiated with early planning discussions in 2014 and with field studies conducted during the 2014 through 2016 growing seasons. While preliminary data analyses were conducted and presented at professional scientific meetings, the intent was that each of the graduate students would wait until all 3 yr of the project were completed to finish their degree program thesis or dissertation (phase 2). Concurrent with completion of their degree requirements, the students will be submitting their findings for publication in refereed journals. In the 2017 to 2019 timeframe, it is anticipated graduate students will be submitting manuscripts for journal consideration. While priority has been given to graduate students for first publication, undoubtedly additional investigative ideas will be developed by project investigators that can be tested and will lead to additional scientific contributions (phase 3). This phase potentially could go well past 2020.

Other industry and public research groups have already expressed interest in having access to these data for other analyses and modeling activities. Publication of the raw dataset for others to use is anticipated late in 2020.

Table 5. A summary of working objectives for the graduate student research on this project.

| Graduate student | Thesis or Dissertation objectives |
|---|---|
| Student 1 | Assess the relationship between the response of residual soil nitrate-N and that of corn grain yield to N applied at pre-plant or split between pre-plant and a split application.<br>Assess the relationship between various measures of nitrogen use efficiency (NUE) and residual soil nitrate-N. |
| Student 2 | Compare the performance of publicity available algorithms for making in-season N fertilizer recommendations using canopy reflectance sensing.<br>Explore how weather and soil variables could be used to improve N recommendations from canopy sensing. |
| Student 3 | Assess the impact of pre-plant and split N application strategies on in-season soil nitrate-N availability, N uptake, and yield over various weather and soil conditions.<br>Compare the effect of soil sampling timing, N fertilizer rate, incubation length, site characteristics, incubation length, and their interactions on potentially mineralizable nitrogen (PMN).<br>Quantify the predictive power of PMN values at different soil sampling timings and N rates alone and in conjunction with site characteristics and/or the pre-side-dress soil nitrate-N test or pre-plant soil nitrate-N test in determining soil N, plant N uptake, optimal N rate, and yield. |
| Student 4 | Evaluate and compare over a wide range of soil and weather conditions in the U.S. Midwest publicly available N decision tools for making corn N rate recommendations.<br>Assess publicly available N decision tools for minimizing residual post-harvest soil nitrate-N.<br>Investigate improving N decision tools by adjusting N fertilizer recommendations with site-specific soil and current-season weather information.<br>Explore improving N decision tool performance by combining or fusing tools together. |
| Student 5 | Assess internal nitrogen efficiency response (IE) to N rate and application timing.<br>Evaluate the effect of each component that make up IE and determine their contribution to it overall value.<br>Evaluate soil properties, weather, and crop sensing technology ability to predict IE at economic optimal nitrogen rate (EONR). |

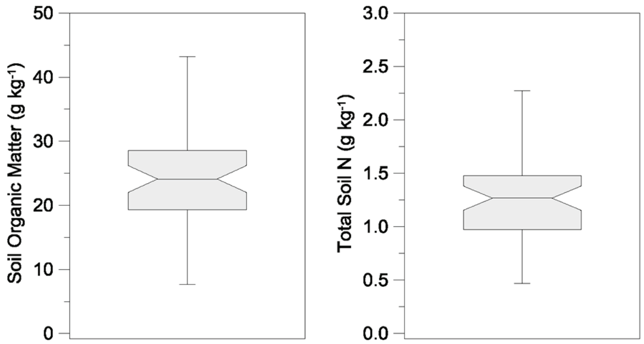


Fig. 3. (left) Soil organic matter and (right) total soil N from the surface ~0 to 40 cm soil for the 49 research sites. The box midline represents the median, the box notch represents the 95- confidence interval around the median, the upper and lower edges of the box represent the 25 to 75 percentiles, and the whiskers represent the range.

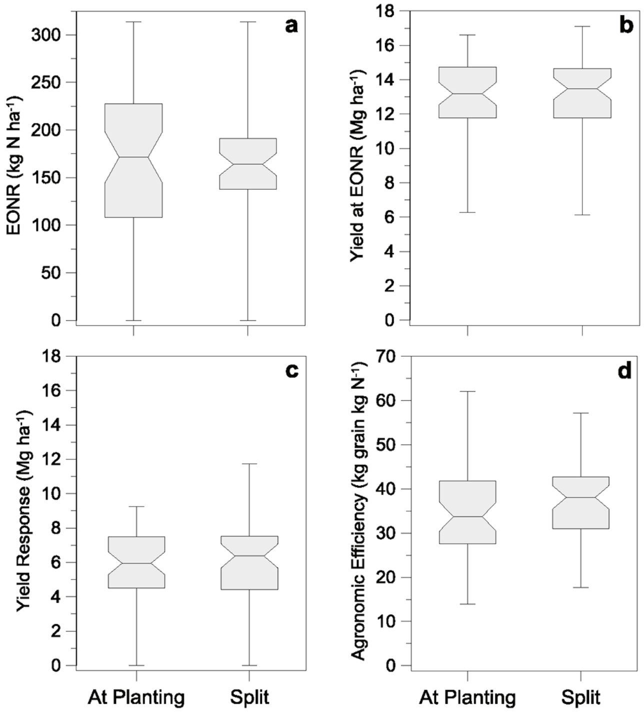


Fig. 4. (a) Economic optimal nitrogen rate (EONR), (b) yield at EONR, (c) yield response from N to EONR, and (d) the agronomic efficiency of EONR for the 49 research sites when all N was applied at planting (Planting) or when split applied (45 kg N ha$^{-1}$ at planting and the remainder at the V9 development stage). The EONR value for each site was calculated using a corn price of \$0.157 kg$^{-1}$ and an N fertilizer price of \$0.88 kg$^{-1}$ after fitting the yield data to either a quadratic-plateau, quadratic, or linear model. In the plots the box midline represents the median, the box notch represents the 95-confidence interval around the median, the upper and lower edges of the box represent the 25 to 75 percentiles, and the whiskers represent the range. Only 46 sites were used for agronomic efficiency of EONR (lower right); the three situations for each fertilization time where EONR = 0 were removed.

## Project Advantages and Value

Several advantages have occurred because of the way the research project was conducted. In recent decades, federal research funding is often coupled with the requirement of multidisciplinary approaches and wide-ranging objectives. The strength of such funded research is the breadth and interactions of the research questions as it often represents diverse biological, economic, and sociological interests. A disadvantage is the inability to focus resources on a specific need. In this case, there was a specific need identified, within the U.S. Corn Belt, which was shared by an agricultural company and by the public (as represented by land-grant university soil fertility research and extension programs). Both entities desired detailed corn N response information over a wide range of soil and weather conditions, and with consistent research protocols. Use of public funds for this type of research has diminished in recent decades for many reasons, but generally applied field research of this nature has not been a funding priority. For this particular research the source of funding was an excellent match for the desired goals.

A second example of conducting research in this manner was the unified effort of including all the principal investigators in the early stages of protocol development, including describing project organization, roles, coordination, and communication. This development phase was essentially complete before initiating studies in the field. Including the extensive experience of all investigators in a Delphi method approach (Dalkey and Helmer, 1963) resulted in a plan with shared ownership and enhanced the team's confidence in the research effort.

A third advantage was the reduced bureaucracy and paperwork for project approval, project administrative costs, agreements, dispersal of funding, equipment and laboratory expenditures, and result reporting compared to the process typically experienced with publicly funded projects. For example, as mentioned above, many equipment purchases and all laboratory costs were coordinated and centralized as a single purchase through the funding industry partner. This approach resulted in improved cost and time efficiency than if the funds had been distributed to individual universities with each making purchases using their individualized procurement procedures. While accountability for completing research using sound scientific methods is necessary, requirements imposed by some funding sources have become so arduous that securing and then managing the research resources can stifle research itself.

Another advantage has been the unique perspectives and strengths the investigators across the eight states have contributed to critical and creative thinking. The recognized co-equal voice given to all the principal investigators has also helped balance investigator biases. Because of the breadth in perspectives, graduate student training has been enhanced by both expertise and geographic scope.

Finally, the extensive planning, regular communication, mutual respect, and good personal nature between the industry and public team members have promoted cooperation, flexibility, and trust. The resultant "good chemistry" within this team has facilitated interaction and productivity. Not all teams have such positive interaction, which can hinder their efficacy.

## CONCLUSIONS

Agronomic investigations to explore the interactions of genetics (G) × environment (E) × management (M) (G×E×M) are fundamental for addressing the grand challenge of supplying food, feed, fiber, and fuel for a growing global population while also improving environmental stewardship. The complexity and enormity of G×E×M interactions are justification of big data collection, inquiry, and innovation. This project is an example of how the interacting "environment" and "management" parts of the G×E×M framework were explored when evaluating corn N response when fertilization was at planting and split applied over a wide geographic range of soil and weather conditions. The results will also allow for simultaneous validation of decision tools used in making corn N fertilizer recommendations. While this study focused on N rate and timing questions for the U.S. Midwest, these results and the way they were generated provide a road map for similar studies. Further, the findings will likely have far reaching effects for modifying or developing new N fertilizer management tools globally.

The impact of fertilizer N use in corn has profound economic and environmental consequences. Growers have become more educated to these consequences and seem eager to have user-friendly tools to assist them in their fertilizer decisions. But unless these tools are scientifically proven with field experimentation and validation, such as generated by this research, then the experience of growers can lead to skepticism and rejection.

It has been shown that when public-industry research collaboration carefully considers and protects the interests of all sides, both innovation and technology transfer can result that benefits everyone (Wright et al., 2014). The public-industry collaborative arrangement of the project has thus far proven highly productive, and aspects of this project could be modeled when organizing similar projects, particularly those that have a regional scope.

## ACKNOWLEDGMENTS

This research was made possible by funding from DuPont Pioneer. The authors would like to thank other supporting scientists (Matt Yost and Kristen Veum [MO]; Dan Barker [IA]; Lakesh Sharma, Amitava Chatterjee, and Norm Cattanach [ND]; Todd Andraski [WI]; and Tim Hart [DuPont Pioneer]) field technicians (Matt Volkmann [MO]; Jason Niekamp and Joshua Vonk [IL]; Glen Slater [NE]; Andrew Scobbie, Thor Sellie, Nicholas Severson, Darby Martin, and Erik Joerres [MN]), and the cooperating farmers and research farm personnel.

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