FACTORS AFFECTING INTERNAL NITROGEN EFFICIENCY OF CORN

by

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To God, my wife, and parents

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ABSTRACT

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Internal N efficiency (IE) is defined as the amount of grain dry matter (GDM) produced per unit of N in the above ground plant at physiological maturity (PMN). Currently, a static value of IE (48 kg GDM kg^{-1} N) is used to define the optimal PMN in yield goal-based N recommendations used in 30 U.S. states and several N recommendation models. To evaluate the accuracy and variability of this value of IE at the economic optimum N rate (IE_E), experiments were conducted at 47 sites located in eight states over a three year period (2014-2016). To establish IE_E, N treatments ranged from 0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments, applied either at-planting or split with 45 kg N ha^{-1} at-planting and the remainder at the V9±1 V-stage. Average IE_E across all site-years was 53 kg GDM kg^{-1} N with 79% of the observations between 46 and 60 kg GDM kg^{-1} N, higher than the currently accepted value of IE. Half of the time the timing of N application affected IE_E, with greater IE_E with split N in 70% of these instances due to lower PMN arising from reduced stover dry matter. In most cases the timing of N did not affect IE_E. Across all site-years, GDM at the EONR or EONR were unrelated to IE_E. Plant N content at VT of the non-fertilized and 45 kg N ha^{-1} at planting treatments were single variables most highly correlated with IE_E ($p \leq 0.10$, r = -0.42 and -0.50, respectively). These variables reflected the amount of residual or available N retained in the plant and/or SDM at the optimal N rate. Other factors such as plant available water content at various depths and crop reflectance at the V9 leaf stage (sufficiency and simple ratio indices for both NDVI and NDRE at 0 and 45 kg N ha^{-1}) were negatively related to IE_E across all site-years, but only weakly. Predictive models for IE_E at planting and prior to sidedressing accounted for < 50% of the variation in IE_E. Internal N efficiency varied considerably, but was difficult to predict, thus contributing to the inaccuracy of the yield-goal based N recommendations.

CHAPTER 1. LITERATURE REVIEW

1.1.1 Introduction

Corn (*Zea mays* L.) was domesticated approximately 10,000 years ago in southern Mexico (Piperno and Flannery, 2001). Europeans first discovered corn in 1492, when Columbus landed on Cuba; thereafter, corn production spread to other parts of the world (Gibson and Benson, 2002). Today corn is one of the most important cereal crops for both human and animal consumption and is grown as a grain, forage, and biofuel. Since 1994, more corn grain has been produced annually than any other cereal crop (FOASTAT, 2017). World production was ~1.1 billion tons of grain generated from ~197 million hectares in 2017 (FAOSTAT, 2017).

For over two decades, corn has been grown in the U.S. on at least 28 million hectares, however, from 2013 to 2017 corn acres have declined from 35 to 33 million hectares (FAOSTAT, 2017). Corn production in the U.S. accounted for approximately 17% of all harvested hectares and more than 32% of the total world corn production in 2017, more than China, Brazil, or Argentina (FAOSTAT, 2017). In recent years, corn prices have fallen due to average U.S. corn yield near or above record highs (10,732 kg ha^{-1}) and lower demand for biofuel production and lower feed prices (USDA-National Agricultural Statistics Service, 2016). This has led to greater incentive for growers to increase the efficient use of inputs and improve profit margins.

1.1.2 Corn Growth and Development

Understanding the processes involved in corn growth and development helps to understand how specific factors, such as stresses, influence the plant. Timing of stress affects the amount of damage and yield loss incurred by the plant. Input applications and scouting schedules are needed to mitigate plant stress, which are scheduled around specific growth stages. A field is classified at a specific growth stage when at least 50% of the field has reached the same growth stage (Abendroth et al., 2011). Corn plants express a determinate growth habit, which means vegetative structures (leaves and stalk) are developed before the onset of reproductive structures (tassel and ear). There are several steps that occur during vegetative growth such as establishment, photosynthetic leaf area production, meristem formation, and potential sink size (kernels ear^{-1}) determination (Abendroth et al., 2011). It is important during this stage for corn to accumulate majority of its N, however, if N availability is limited during this time corn can compensate by increasing N uptake after silking (Woli et al., 2017).

During early growth stages, tillers and ears are indistinguishable to the naked eye. The genetic makeup and hormones produced by the corn plant determine whether a tiller or ear is produced by the axillary meristem. As corn develops, the axillary meristem produced tillers on the lower five to seven stalks nodes and ear shoots on higher stalk nodes. At the V5 stage, the harvestable ear (female reproductive structure) is initiated and is typically found on the 12^{th}, 13^{th}, or 14^{th} stalk node. Ears below the harvestable ear typically do not fully develop due to hormonal balances and farther distance from the photosynthesizing leaves during grain fill (Nielsen, 2014). The apical meristem (growing point) produces leaves and the male reproductive structure called the tassel, which is also initiated around V5. The early initiation of the male and female reproductive structures leaves them sensitive to above ground stresses from biotic (weed, insect, and disease damage) and abiotic factors (nutrient deficiency, temperature, hail, wind, wheel traffic, and chemical injury). Thus, stress factors can reduce root and leaf area and lead to decreased kernels row^{-1} (sink strength) before pollination occurs (Lejeune and Bernier, 1996; Nielsen, 2000). The maximum number of kernel rows are set around V7 and are unlikely to change due to stress, since the plant's genetics strongly influence row numbers (Abendroth et al., 2011). The development of kernels are initiated from the base to the tip of the ear (Cárcova et al., 2003). Each ear has around 700 to 1000 potential kernels, however, only 450 to 550 kernels develop and survive to harvest (Abendroth et al., 2011). During the growth stages between V7 and V15, the occurrence of stress can negatively affect the potential kernels row^{-1} (Nielsen, 2007). Once the plant has reached approximately one week before silk emergence, the maximum number of potential kernels row^{-1} are completely developed.

The maximum number of leaves and height is reached at tasseling (VT) and shortly after, photosynthate is partitioned to the grain (Nielsen, 2010). The next growth stage occurs when the silks emerge from the husk, which is called the silking stage (R1). This stage can occur before VT, since hybrid improvement has caused these two stages to be more synchronized. During the R1 stage, corn is at a greater risk of being affected by environmental stresses, which influences the number of kernels ear^{-1}. The occurrence of environmental stresses can throw off the synchronization between pollen shed and silk emergence. Most of the time drought stress leads to delayed silk elongation and acceleration of pollen shed. Nitrogen stress can also delay silk elongation (Lemcoff and Loomis, 1994) and timing of flowering (Hanway, 1962). After pollination, N uptake gradually slows and shifts toward stored N in the vegetative tissue to meet grain N needs, thus, the corn plant begins to senesce (Nielsen, 2000). Increased stress causes enhanced dependence on stored N reserves and increases the rate of senescence. The corn ear has reached 40-45% of its final length by the R1 stage and is beginning to enter rapid elongation. After R1, fertilized ovules are still affected by stress and run the risk of being lost due to abortion. The potential for abortion occurs from R2 (blister) to R3 (milk) stage, when there is insufficient supply of carbohydrates and N. The limitation of N causes kernel abortion due to increased leaf senescence and lower photosynthate production. Once the plant has reached R4 (dough) stage, stress cannot cause kernel abortion, but can reduce kernel weight due to decreased starch accumulation. Approximately 45% of the final kernel weight has accumulated by R5 (dent) stage (Abendroth et al., 2011). During R5 stage, final kernel weight is 90% complete by half milk line (Afuakwa and Crookston, 1984; Ma and Dwyer, 2001). The next growth stage is R6 (physiological maturity) indicated by the formation of a black layer at the base of the kernel, which indicates the maximum amount of kernel dry matter has accumulated. Once this stage has been reached, environmental stresses have no effect on final grain yield (Abendroth et al., 2011).

1.1.3 Improvement in Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) is often defined as the ratio of the amount of grain produced to the amount of fertilizer N applied to the soil (Moll et al., 1982). Moll et al. (1982) further broke down NUE into two main components, uptake efficiency (plant N content/N fertilizer applied) and utilization efficiency (grain weight /plant N content). These components account for the plant’s ability to efficiently take up N fertilizer and utilize it to produce grain. Since the green revolution (1950 – 1960), higher N rates are needed to increase corn yields which has led to greater potential for N loss and low NUE (Cassman et al., 2002). The reduction in NUE is largely contributed to excess supply of N either from fertilizer and/or the soil (Meisinger et al., 2008). Thus, it is important to accurately estimate optimal N rates to decrease the negative affects to the environment and increase grower profitability.

1.1.3.1 Fertilizer Inputs

The three major cereal crops (rice, wheat, and corn) use about 50% of global N fertilizer with corn production accounting for about 17% (Heffer et al., 2013). Currently world N fertilizer consumption is about 193.3 million metric tons and is projected to increase with the growing population (FAO, 2017; Raun and Schepers, 2008). If the world population reach the projected amount of 9.6 billion by 2050, then grain production will need to increase around 50 to 70% to meet global demand (Raun and Schepers, 2008). From 1961 to 2004, the ratio of cereal grain to N fertilizer applied fell from 120 to 40 Mt grain Mt^{-1} N applied (Raun and Schepers, 2008). Therefore, increased potential for N contamination and decreased NUE occurred during this period. Meeting this demand will require increased NUE to maintain or increase yield while decreasing impact on the environment (Ladha et al., 2005).

1.1.3.2 Environmental Impact of Nitrogen

To meet the growing population's food and energy needs, more N fertilizer has been used to increase crop and fuel production. The increased use of N fertilizer has led to changes in the N cycle and its effects on water and air quality (Galloway et al., 2004). Concerns over drinking water quality and its impact on health have increased in agricultural areas due to elevated NO_3^- levels. Approximately 42% of the U.S. population uses well water as their main drinking source, and about 22% of these wells are above the maximum NO_3^- level (10 mg L^{-1} NO_3-N) (Ward et al., 2005). Increase N levels have also been found in rivers, streams, and oceans and has led to eutrophication resulting in increased algae growth, thus, causing anoxia or hypoxia environments in the lower depths of the water. Decreased oxygen can cause aquatic plant and animal death and reduce aquatic plant and animal diversity over the long term (Vitousek et al., 1997).

The world's air quality has also been reduced from the amplification of microbial processes, such as nitrification and denitrification, due to the inefficient use of N fertilizer. These two microbial processes can result in the release of N_2O into the atmosphere. The presence of N_2O in the atmosphere damages the protective ozone layer that shields the earth from ultraviolet radiation (Blackmer and Bremner, 1978). The aerobic nitrification process releases smaller amounts of N_2O compared to denitrification which occurs under anaerobic conditions (Blackmer and Bremner, 1978; Weier et al., 1993). Another possible result of incomplete denitrification, NO, affects air quality by elevating ground level ozone and acid rain (Galloway et al., 2004; Vitousek et al., 1997). However, complete denitrification to N_2 is not harmful to the atmosphere, because it is non-reactive and is reused in the N cycle (Bobbink et al., 2010).

1.1.3.3 Economics of Nitrogen Fertilization and Nitrogen Recommendations

In 2016 in Indiana, the estimated total variable cost (fertilizer, seed, pesticide, fuel, etc.) on an average productivity soil in a corn-soybean rotation was \$1,060 ha^{-1} (Dobbins et al., 2016). About 31% of the total variable cost was fertilizer, and N made up the largest portion of the fertilizer cost. From 1995 to 2004, N fertilizer was less expensive (\$0.28 to \$0.54 kg^{-1} N) (USDA-ERS, 2016) and the affordable price may have resulted in over-application of N fertilizer to avoid N deficiency that may occur during the growing season. With increased N fertilizer cost, efforts are needed to improve growers' return on this input. This has sparked many companies to develop N recommendation tools to predict more economical N rates that would help growers generate better return on N inputs. Most of these tools use an estimate of yield to calculate N rate. Past research (Sawyer et al., 2006) has indicated that optimum yield does not correlate with economic optimum N rate (EONR), which is the N rate needed to produce the most profitable yield. These tools were also developed under the idea that the amount of N needed to produce a kg of grain was constant at 0.021 kg N kg^{-1} grain. This idea originates from Stanford (1966), where it was determined N requirements were not affected by changes in environment, management practices, yield level, and corn genotypes to achieve maximum yield. However, more recent research (Ciampitti and Vyn, 2012) found N requirements (per kg of N in the plant) in corn genotypes from 1991 to 2011 to vary from 0.01 to 10 kg N kg^{-1} grain across environments, management practices, yield level, and corn genotypes. Other research (Sawyer et al., 2006) has also shown poor calculated adjustments for non-fertilizer inputs with yield-based N recommendations. Currently, there has been a push to select N rates based on historical data obtained from multiple years of N response trials conducted in each specific state (Camberato and Nielsen, 2015; Sawyer et al., 2006).

1.1.4 Corn Nitrogen Dynamics

The process of uptake, assimilation, and remobilization of N determines a corn plant's ability to utilize and convert N into stover and grain dry matter, which influences the components of NUE. The level of contribution each component has on overall NUE varies with plant genotypes and environment conditions (Moll et al., 1982). Therefore, it is important to understand how these processes function and vary during plant growth and under different environmental conditions.

1.1.4.1 Nitrogen Uptake

In corn production, N is the most common limiting nutrient, thus deficiency has a large impact on grain yield. The uptake of N occurs through root interception, diffusion, and mass flow, which accounts for 1, 20, and 79%, respectively, of N taken up by the plant (Barber, 1995). During the first 30 days of growth, N uptake is slow and is derived from the seminal root system, which consists of the radicle and lateral seminal roots (Nielsen, 2013). The seed reserves are the main source of nutrients until V3, which begins the transition to the nodal root system. By V6, the nodal roots are the main source for nutrients and water uptake (Nielsen, 2013). During the V10 to V14 stage, maximum plant N uptake occurs, with rates as high as 8.93 kg N ha^{-1} day^{-1} (Bender et al., 2013). By R1, several studies found 65% of the total N has been accumulated in the plant (Abendroth et al., 2011; Bender et al., 2013; Doerge et al., 1991; Scharf and Lory, 2006) while more recent studies found about 59 to 78% of the total N accumulated by R1 (Mueller et al., 2017, Woli et al., 2017). During the grain fill period, less photosynthate is translocated to the root system due to the grain's high demand for photosynthate, thus, N uptake is reduced to ~1.13 to 2.25 kg N ha^{-1} day^{-1} (Ciampitti and Vyn, 2011; Pan et al., 1986). Maximum N has accumulated in non-grain plant parts by approximately R2 (Abendroth et al., 2011; Doerge et al., 1991; Mathews, 2001).

Many environment factors influence the plant's ability to take up N. Water availability impacts two of the main processes (mass flow and diffusion) involved in N uptake. These processes require water to move N and other nutrients into the plant roots where it is assimilated and translocated to other plant parts (Fageria, 2009). However, excess water can decrease N uptake by reducing soil oxygen needed for respiration, which impacts water movement in the plant (Wiebold, 2013). Soil texture also affects N uptake by influencing drainage and N availability. Fine-textured soils remain saturated longer than coarse-textured soils resulting in greater potential for N loss through denitrification. Water holding capacity is less in coarse-textured than fine-textured soils, which increases N loss via leaching (Van Es et al., 2005). Management practices also influenced the amount of N the plants can accumulate. Higher plant density (54,000 to 104,000 plant ha^{-1} in 25,000 plant ha^{-1}) at higher N rates (0, 165, and 330 kg N ha^{-1}) can increase N uptake (54,000 [124 to 195 kg N ha^{-1}], 79,000 [131 to 211 kg N ha^{-1}], and 104,000 plant ha^{-1} [136 to 235 kg N ha^{-1}]) (Ciampitti and Vyn, 2011). One of the most critical management decisions is timing of N applications, which affects the amount and efficiency of N uptake. In humid climates or wet springs, sidedress N application increase N uptake since there is lower potential for N loss (leaching and denitrification) and application is closer to the period of plant maximum uptake (Fox et al., 1986; Roy et al., 2014; Sainz Rozas et al., 2004). In western portions of the Corn Belt, pre-plant or at-planting N application can increase N uptake due to dry soil conditions later in the season (Bigeriego et al., 1979; Kovács et al., 2015; Sela et al., 2016).

1.1.4.2 Assimilation

The plant's ability to convert NO_3^- and NH_4^+ into amino acids needed for biomass is termed N assimilation. The predominant form of N used in this process is NO_3^- (Fageria, 2009). Assimilation occurs after NO_3^- has been absorbed into the roots, where it can be assimilated or transported to the shoots for assimilation. Excess amounts of NO_3^- are transported and stored in the vacuoles, which act as a NO_3^- reserve. The first step in assimilation is the conversion of NO_3^- to NO_2^-, which is catalyzed by nitrate reductase enzyme (NRA). An elevated level of NO_3^- in tissue induces NRA levels to increase. Nitrite is transported into the leaf's chloroplast where energy (~15 ATP mol^{-1}) is required for the NRA to convert NO_2^- into NH_4^+. However, energy needs are reduced when plants take up NH_4^+ since it can be directly assimilated into amino acids (Fageria, 2009). Amino acids are then utilized to produce new plant tissue or other cellular structures (Dubey et al., 2014).

Water and temperature stresses influence N assimilation by affecting the rate of plant growth, N uptake, and the activity of N assimilation enzymes. The level of N assimilation is often quantified by determining the activity of nitrate reductase enzyme (Beevers and Hageman, 1969), which is the rate-limiting step to N assimilation (Hageman, 1979). During water stress conditions, corn plants show reduced NRA due to low water potential in the leaf, decreasing NO_3^- flux and reducing transport of NO_3^-. Nitrate reductase activity and N assimilation are reduced when temperatures exceed the optimum temperature range for corn growth (25-30˚C) (Singh and Sawhney, 1989). Other environmental factors affecting N assimilation are light (intensity and duration), soil salinity, and metal toxicity (Dubey et al., 2014).

1.1.4.3 Remobilization

The optimal combination of N assimilation and remobilization efficiency are important in determining one of the main components of NUE, N utilization efficiency or internal N efficiency (IE) (Moll et al., 1982; Pollmer et al., 1979). The uptake and remobilization of N has more impact on grain yield and NUE at low N supply than at high N supply (Friedrich and Schrader, 1979; Moll et al., 1982). As the corn plant matures, recycling and remobilization of N gradually become the main source of N for grain development. Remobilization of N occurs when photosynthetic proteins in the vegetative tissue are degraded during senescence, which release proteins and other amino acids that are loaded into the phloem and transported to the sink (ear and/or roots). The remobilization of N from stover components accounts for 60 to 85% of grain N, while the remaining grain N comes from N uptake after silking (Olea et al., 2004; Pan et al., 1986; Ta and Wieland, 1992).

Early onset of remobilization is caused by environmental stresses such as pathogen attack or limitation in N supply (Nielsen, 2011). Early onset of N remobilization can occur with low N availability during the growing season and vary with different corn genotypes (Chevalier and Schrader, 1977; Friedrich and Schrader, 1979). This results in N being scavenged from vegetative parts to fill grain photosynthate needs or protect healthy plant parts from invading pathogens (Ma and Dwyer., 1998; Olea et al., 2004). Remobilization is also influenced by the sink strength of the ear, which becomes the highest priority during grain fill. Increased ear sink strength can occur with the production of a second ear, which increases N remobilization from the stalk and roots. However, fertilization of a second ear may reduce N uptake during the grain fill period due to decreased leaf area and photosynthesis (Pan et al., 1986; 1995).

1.1.5 Components of Nitrogen Use Efficiency

Nitrogen use efficiency is the amount of grain produced per unit of N fertilizer applied to the soil (Moll et al. 1982). However, other ways have been used to calculate NUE to account for the N contributed by the soil compared to Moll et al., (1982) definition of NUE. In cropping system research, NUE is used to evaluate the plant's ability to efficiently take up and convert N fertilizer into grain yield (Cassman et al., 2002). However, more useful information is obtained on the variation in management practices and economic return by splitting NUE into its two main components of N uptake efficiency (NU_PE) and IE due to physiological mechanisms and process that affect NUE (Cassman et al., 2002; Moll et al., 1982; Salvagiotti et al., 2009).

1.1.5.1 Nitrogen Uptake Efficiency

Over the last 30 years, improvements in production and N fertilizer management along with increases in hybrid yield and stress tolerance, has improved NU_PE (Cassman et al., 2002, Mueller and Vyn, 2016). Further improvement in NU_PE will be made with continued reduction in fall N applications, while moving away from large single application and towards lower split applications (Vetsch and Randall, 2003). Also, the incorporation of techniques for determining optimum N rate such as soil N testing (Vanotti and Bundy, 2013), crop reflectance sensors (Delgado and Bausch, 2005), and crop development modeling (Rimski-Korsakov et al., 2004) may help improve NU_PE. Recent hybrids studies are looking for ways to improve hybrids NU_PE by enhancing root architecture across a wide range of environments (Torres et al., 2018; Zhang et al., 2018).

1.1.5.2 Internal Nitrogen Efficiency

Internal N efficiency is the ability to utilize previously accumulated N to produce grain (Moll et al., 1982). The level of IE has been found to range between 30 to 70 kg grain kg^{-1} N under low N availability (Bänziger et al., 2000). The implementation of management practices and genotypes used by farmers affects IE (Kamprath et al., 1982). Other factors causing stress on the plant (nutrient deficiencies other than N, drought and heat stress, mineral toxicities, and pest damage) can reduce IE by decreasing crop growth and the plant's ability to efficiently utilize previously accumulated N to produce grain (Cassman et al., 2002). However, reductions in N availability increase IE, thus, very high IE may indicate N deficiency (Dobermann, 2007). Alternatively, low IE may indicate luxury consumption of N caused by reduced sink strength (Muchow, 1998). Physiological mechanisms involved in tissue formation affect IE by influencing the amount of N remobilized and translocated to the grain (Novoa and Loomis, 1981).

1.1.6 Genetic Influence on Internal Nitrogen Efficiency

1.1.6.1 Hybrids

During the Green Revolution (1950 – 1960s), high yielding varieties of corn, wheat, and rice were selected to respond to high N inputs, thus, little improvement was made in overall NUE (Earl and Ausubel, 1983). In the US, higher N fertilizer rates and poor management practices decreased NUE (kg grain yield kg^{-1} N fertilizer) until the 1970's when more efficient management practices and higher yields began to increase NUE (George, 2014; Lassaletta et al., 2014; Zhang et al., 2015). By 2010, overall NUE increased to approximately 68 kg grain yield kg^{-1} N fertilizer. Continued improvements in NUE will occur with better refinement of management practices and genetic selection. Hybrids with traits that can be used to improve NUE are easier to identify under low N supply (Anderson et al., 1985). The selection of hybrids under high N supply masks differences in NU_PE and IE by allowing hybrids with poor NU_PE and IE traits to acquire enough N for growth and development (Kamprath et al., 1982). However, selection under low N supply is not widely practiced in agricultural experiment stations and breeding programs (Raun and Schepers, 2008). A corn hybrid study noted IE did not differ between hybrids selected for better performance under low (24 hybrids) and high N supply (25 hybrids) (Presterl et al., 2002). However, hybrids selected under low N supply at the 0 and 100 kg N ha^{-1} had higher grain yield (5,066 and 6,639 kg grain yield ha^{-1}) and N uptake (97 and 138 kg N ha^{-1}, respectively) than hybrids selected under high N supply (grain yield: 4,538 and 6,304 kg ha^{-1}, N uptake: 86 and 130 kg ha^{-1}, respectively). There was no difference between low or high N supply hybrids at 200 kg N ha^{-1}. Across all 49 hybrids, IE decreased with higher N rates from 51 to 41 kg grain yield kg^{-1} N. For hybrids selected under high N supply, IE and N uptake were positively correlated at 0 kg N ha^{-1} (r = 0.48, $p \leq 0.05$), but negatively correlated at 200 kg N ha^{-1} (r = -0.59, $p \leq 0.05$). This suggest that the use of high N supply would only improve one component (N uptake or IE) while the other would be reduced. However, the positive correlation of N uptake and IE with low N supply suggest both would be improved without a reduction in either component. Grain yield correlation with N uptake (r = 0.85, $p \leq 0.05$) and IE (r = 0.86, $p \leq 0.05$) at 0 kg N ha^{-1} indicates indirect selection for higher grain yield would improve IE and N uptake. Another study found IE did not vary among twelve hybrids grouped into different eras (1970s, early 1990s, and late 1990s) (O'Neill et al., 2004). However, there was significant variation in IE among all hybrids, which varied from 44 to 68 kg grain DM kg^{-1} N across water (deficit and adequate) and N treatments (0 and 200 kg N ha^{-1}). The wide range in IE across all water and N treatments occurred due to the negative correlation of IE and N uptake (r = -0.73, $p \leq 0.01$). However, this relationship was positive (r = 0.79, $p \leq 0.01$) when selected under low N availability. Thus, suggesting improved IE when selection occurred under low N availability. In contrast, in three open pollinated populations NU_PE and IE contributed equally to variation in NUE under low (56 kg N ha^{-1}) and moderate N supply (168 kg N ha^{-1}) (Kamprath et al., 1982). Internal N efficiency accounted for all of the variation in NUE under high N supply (280 kg N ha^{-1}). Therefore, populations improved under moderate N supply favored improvements in IE. However, other studies are in support of the conclusion of greater improvement in IE under low N supply than high N supply (Lafitte and Edmeades, 1994; Moll et al., 1982).

Research conducted to evaluate factors influencing IE found variations in N accumulated at silking, N translocated to the grain, and N remobilized from vegetative tissue differed between hybrids under varying N supply. Variation in IE among eight open pollinated varieties was found most pronounced under low N supply (56 kg N ha^{-1}) (Moll et al., 1982). Internal N efficiency among these populations varied from 35 to 59 kg grain DM kg^{-1} N and 32 to 48 kg grain DM kg^{-1} N under low and high N supply, respectively. The ability of a variety to achieve high IE varied in their physiological process such as changes in N accumulated at silking, N remobilized, and grain N concentration (Ng). Another study noted an interaction between twelve hybrids and four N rates (0, 78, 157, and 235 kg N ha^{-1}) with IE due to hybrids variations in N uptake at midsilk among N rates. However, IE did not differ among hybrids across N rates (39 to 49 kg grain yield kg^{-1} N) (Bundy and Carter, 2013). Internal N efficiency varied from 51 to 56 kg grain yield kg^{-1} N and 41 to 50 kg grain yield kg^{-1} N at 67 and 402 kg N ha^{-1}, respectively, among four different corn hybrids (Tsai et al., 1992). The difference in hybrid’s ability to achieve higher yields under low N condition may contribute to the variation in IE among hybrids.

Corn genotypes released from 1991 to 2011 had higher IE (55 kg grain yield kg^{-1} N) compared with genotypes from the 1940s to 1990s (49 kg grain yield kg^{-1} N) (Ciampitti and Vyn, 2012). Internal N efficiency was also higher for hybrids from the 2000s (66 kg grain yield kg^{-1} N) compared to 1960s (48 kg grain yield kg^{-1} N) when evaluated at 168 kg N ha^{-1} (Woli et al., 2016). The increase in IE from old to new genotypes was largely due to a decrease in Ng (Ciampitti and Vyn, 2012: 13.3 to 11.9 g kg^{-1}; Woli et al., 2016: 16.1 to 12.3 g kg^{-1}). The reduction of Ng in new era genotypes was due to a 36 g $plant^{-1}$ decrease in biomass and 1 g N $plant^{-1}$ decrease in N uptake at silking, thus indicated further advancement in IE entail greater N uptake pre-silk and improved remobilization of N during mid-grain fill (Ciampitti et al., 2013). The improved IE was also due to greater population density (categorized into low [10,000 to 50,000 plant ha^{-1}], medium [50,000 to 80,000 plants ha^{-1}], and high populations [80,000 to 110,000 plants ha^{-1}]), N deficiency tolerance, and increased yield response to N inputs in new era genotypes (Ciampitti and Vyn, 2012). Grain yields under zero and high N supply (250 kg N ha^{-1}) for new genotypes were 800 and 2,000 kg ha^{-1} greater than that of old era genotypes. However, on a per plant basis old era genotypes yielded greater than new era genotypes by 12 g plant^{-1}. Nitrogen uptake at maturity did not differ between old (2.9 g N plant^{-1}) and new era genotypes (2.4 g N plant^{-1}).

1.1.7 Influence of Plant Processes on Internal Nitrogen Efficiency

Absorption, assimilation, and remobilization of N by the plant influences NU_PE and IE. Hybrids vary in these processes to achieve higher overall NUE and IE (Moll et al., 1982). Improvements in IE have also resulted from reduction in Ng (Ciampitti and Vyn, 2012; Muchow, 1998; Woli et al., 2016). Therefore, our focus will be on N assimilation, N accumulation by VT, N remobilization, and Ng.

1.1.7.1 Nitrogen Accumulation at Tasseling (VT)

The amount N available during vegetative growth stages is an important factor for higher IE due to its connection to grain components (potential kernel numbers and weight). The number of kernels in corn genotypes released from 1967 to 2006 was correlated with IE ($r = 0.75$, $p \leq 0.001$) (Haegele et al., 2013). In a greenhouse study with three corn hybrids, withholding N from V8 to maturity or seeding to V8 resulted in a ~25 to 30% reduction in kernel number and a ~22% decrease in kernel weight for both treatments compared to not withholding N (Subedi and Ma, 2005). There were no significant reductions in kernel numbers and weight when N was supplied throughout the vegetative stage compared to N withheld from silking to maturity, 3 weeks after silking, or not withholding N. Nitrogen uptake was largely reduced when N was restricted after V8, which shorten the availability of N during maximum uptake at V10. Another study noted, waiting until V6 to apply N reduced grain yield compared to a V2 N application (Binder et al., 2000). Larger reductions in grain yield occurred when N was delayed beyond V6 (1 to 10% reduction in grain yield) compared to N application at V12, V16, VT, R1.5, R3, and R4.5. The reduction in grain yield increased as the duration of N deficiency increased. One of the reasons grain yield was reduced with late N application was two-thirds of corn N is normally taken up by the onset of reproductive stages (Bender et al., 2013). Therefore, decreases in the amount of N accumulated during the vegetative stage not only decreased grain components and yield, but also impacted IE due to reduced sink strength (kernels per ear) (Haegele et al., 2013).

1.1.7.2 Nitrogen Assimilation

Several processes are involved in efficient NU_PE and IE such as absorption, translocation, assimilation, and remobilization (Moll et al., 1982). After N is absorbed, the assimilation process converts NO_3^- or NH_4^+ into amino acids, which are used to build plant biomass (Masclaux-Daubresse et al., 2010). Nitrate reductase activity (NRA) is the first enzyme in the N assimilation process and its activity is used to monitor the level of N assimilated. The level of NRA was not correlated with IE nor NU_PE among seven sorghum (*Sorghum bicolor* L.) genotypes evaluated under two N rates (0 and 100 kg N ha^{-1}) (Traore and Maranville, 1999). In corn, IE did not differ between hybrids selected for low and high NRA across N rates of 112, 224, and 336 kg N ha^{-1} (Eichelberger et al., 1989). However, IE was higher in both high and low NRA hybrids at 112 kg N ha^{-1} compared to the two higher N rates. Grain N content and stover dry matter and N concentration were lower in low NRA hybrids than in high NRA hybrids. There was no correlation found between NRA and NHI with IE. Another study found NRA did not correlate with IE, however, the enzyme important in leaf senescence [glutamine synthetase (GS)] was positively correlated with IE (r = 0.28, $p \leq 0.05$), grain yield (r = 0.25, $P \leq 0.01$), and number of kernels (r = 0.21, $p \leq 0.05$) under low N supply (Hirel et al., 2001). Although, under high N supply (175 kg N ha^{-1}) GS was not correlated with these variables ($p > 0.01$). However, NRA was negatively correlated with grain yield under both high (r = -0.19; $p \leq 0.01$) and low N rates (r = -0.22; $p \leq 0.05$). Other studies have shown remobilization of previously accumulated N from vegetative tissue to be significantly correlated with IE (Hirel et al., 2001; Traore and Maranville, 1999).

1.1.7.3 Remobilization

The amount of N remobilized from vegetative tissue influences IE by changing the ratio between yield and plant N content (Anderson et al., 1985; Eik and Hanway, 1965; Moll et al., 1982). The N harvest index (NHI) is the ratio between grain N content and total plant N content, which is often used to evaluate N remobilized from the vegetative tissue to the grain (Austin et al., 1977). Variation in IE from old (1940s to 1990s) to new era genotypes (1991 to 2011) was weakly correlated with NHI (r = 0.39, $p \leq 0.05$), but largely explained by negative relationship with Ng (r = -0.79, $p \leq 0.05$) (Ciampitti and Vyn, 2012). Wortmann et al. (2011) found a slightly stronger correlation between NHI and IE (r = 0.49, $p \leq 0.05$) and a weaker negative correlation with Ng (r = -0.65, $p \leq 0.05$) when evaluated under three crop rotations (continuous corn (CC), corn-dry bean (CD), and corn-soybean (CS)) and five N rates (CC and CD: 0, 112 or 140, 168 or 196, 224 or 252, and 336 kg N ha^{-1}; CS: 0, 56 or 84, 112 or 140, 168 or 196, and 280 kg N ha^{-1}). In sorghum, IE was significantly correlated with N remobilization (r = 0.75, $p \leq 0.05$) and grain N content (r = 0.72, $P \leq 0.05$) among seven genotypes and two N rates (0 and 100 kg N ha^{-1}) (Traore and Maranville, 1999). Internal N efficiency was not correlated with Ng ($p > 0.05$).

In general, corn remobilizes 60 to 65% of total grain N from stover parts and 35 to 40% from soil and roots (Bender et al., 2013; DeBruin et al., 2013; Hay et al., 1951; Yang et al., 2016). The onset and rate of N remobilization is linked to ear sink strength and N availability. Increased number of ears produced on a single corn plant enhanced N remobilization from 3.51 to 5.00 g N $plant^{-1}$ with the presence of one ear versus two ears, respectively (Pan et al., 1986). Greater amounts of N were remobilized from the stem and roots of a plant with two ears (3.16 g N $plant^{-1}$) than those with one ear (1.69 g N $plant^{-1}$). Nitrogen remobilized from the leaves was unaffected by the number of ears (~1.83 g N $plant^{-1}$). Internal N efficiency averaged across four N rates (56, 112, 168, and 224 kg N ha^{-1}) was greater in prolific (46 kg grain yield kg^{-1} N; 1.8 ears $plant^{-1}$) than semi-prolific (41 kg grain yield kg^{-1} N; 1.4 ears $plant^{-1}$) corn genotypes (Anderson et al., 1985). The production of a second ear in prolific genotypes led to greater amounts of N remobilized from vegetative tissue than semi-prolific genotypes (1.78 and 1.62 g $plant^{-1}$, respectively). Another study found two improved hybrids produced more second ears with increased N rate than the original hybrid (Kamprath et al., 1982). The increased sink strength of the two improved genotypes versus the original hybrid, resulted in greater IE at N rates of 168 and 280 kg N ha^{-1}; 44 versus 38 kg grain yield kg^{-1} N and 55 versus 45 kg grain yield kg^{-1} N for the two N rates, respectively. This data supported the hypothesis advanced by Ciampitti and Vyn (2013) and Hirel et al. (2001) that the level of N stored during vegetative growth impacts sink strength, thus, effecting the amount of N remobilized to the ear during grain fill and influencing the level of grain yield and IE.

The development of stay-green technology largely believed to be due to better resistance to foliar diseases, has reduced the amount of N remobilized from vegetative plant parts during grain fill. However, the availability of N affects the longevity of leaf area for both stay-green and non-stay-green hybrids. Leaf area in plants with low N supply (0 kg N ha^{-1}) declined earlier than with high N supply (168 kg N ha^{-1}) (Eik and Hanway, 1965). Other studies found the loss of leaf area reduced photosynthate production and the translocation of carbohydrates to the root due to greater demand from the ear sink during grain fill (Starck, 1971; Wardlaw, 1968). A hybrid without the stay-green trait senesced earlier and remobilized 69% of leaf N compared to 44% for the stay-green hybrid averaged across three N rates (0, 100, and 200 kg N ha^{-1}) (Ma and Dwyer, 1998). The stay-green hybrid also had higher NUE compared to non-stay-green hybrids. Higher NUE with stay-green hybrid was observed with 24% higher dry matter and 20% higher N uptake. Photosynthate production was sustained longer by maintenance of leaf N concentration in the stay-green hybrid at each N rate compared to the non-stay-green hybrid. This was attributed to slow rate in decline in leaf area from 2 to 5 wk after silking in stay-green hybrids compared to non-stay-green hybrids. The loss of leaf area limited N uptake and assimilation by the roots due to insufficient energy, thus, decreasing the amount of dry matter accumulated during grain fill, which initiated N remobilization from vegetative tissue.

1.1.7.4 Grain Nitrogen Concentration

Improvements in IE were correlated with decreased Ng. From 1988 to 1994, corn hybrids were shown to have increased yield and decreased Ng, which led to increased IE (Muchow, 1998). Grain protein decreased from old genotypes (1970s; 97 g kg^{-1}) to new genotypes (1990s; 87 g kg^{-1}) (Duvick and Cassman, 1999). Similar results were found in other studies (Ciampitti and Vyn, 2012, 2013). Corn genotypes from the 1940s to 2011 also showed a reduction in Ng over time (13.3 to 11.9 g N kg^{-1}), while IE increased (49.4 to 55.3 kg grain yield kg^{-1} N) over time (Ciampitti and Vyn, 2013). Grain N concentration was the main parameter that changed between old (1940s to 1990s) to new era genotypes

(1991 to 2011) and was a major source of variation in IE over time ($R^2 = 0.62$, $p \leq 0.05$). The amount of variation accounted by Ng increased from 46 to 65% in old to new era genotypes, respectively.

The difference in maturity groups (early vs late) may affect the level of Ng, thus, influencing the level of IE due to the correlation between the two variables. Among 15 corn hybrids, Ng was negatively correlated with hybrid relative maturity rates (76 to 95 days) ($r = -0.60$, $p < 0.02$) (Ma and Dwyer, 2001).

1.1.8 Nitrogen Availability Influence on Internal Nitrogen Efficiency

The main sources of N for plant growth are N fertilizer and N mineralized from soil organic matter (SOM) (Shaver, 2014). The amount and timing of N fertilizer affects the level of N available to the plant, thus influencing yield components (number of kernels) (Uribelarrea et al., 2007) and N accumulation in the plant (Binder et al., 2000). However, other environmental and management factors can affect the level of N available to the plant by impacting the amount of N released from SOM (Akintoye et al., 1999: Griffin, 2008). Therefore, our focus will be on N fertilizer supply, N timing, tillage, population density, soil texture, and water availability.

1.1.8.1 Nitrogen Fertilizer Supply

A number of studies over a wide range of soils, N rates, and hybrids have shown IE decreases with increased N supply (Barbieri et al., 2008; Eghball and Maranville, 1991; Kamprath et al., 1982; Moll et al., 1982; Muchow, 1998). Internal N efficiency decreased in seven of eight corn genotypes with increased N rate (56 vs 224 kg N ha^{-1}) (Moll et al., 1982). In another study, IE of eight corn hybrids decreased from 56 to 42 kg grain yield kg^{-1} N with N rates of 0, 67, 134, 201, 268, and 402 kg N ha^{-1} (Tsai et al., 1992). Similarly, IE was reduced from 63 to 41 kg grain yield kg^{-1} N with increased N over the range of 2, 3, and 5 kg N 1000^{-1} plants (Rhoads and Stanley, 1984).

However, differences in hybrid's ability to convert stored N into grain can improve IE under high N supply. A study with three hybrids (two improved and one original hybrid) noted improved hybrids had higher IE (2 to 13 kg grain yield kg^{-1} N) with increased N compared to the original hybrid (Kamprath et al., 1982). Improved hybrids had greater yield response to N (540 to 1580 kg grain yield ha^{-1}) while differences in total plant N content varied narrowly from -14 to 14 kg N ha^{-1} in the improved hybrids compared to the original hybrid. The enhancement in IE and its components under increased N rates for the improved hybrids was due to the presence of a second ear, which created a stronger sink and elevated remobilization of N from vegetative tissue.

Low N supply resulted in high IE due to greater amounts of N remobilized from vegetative tissue. A greenhouse study using ^{15}N showed that ear development mainly relied on remobilized N rather than N taken up after silking (Friedrich and Schrader, 1979). The remobilization of N was enhanced when N supply was limited causing higher percentage of stored N from the root (67%) and stem (81%) to be utilized compared to when N supply was adequate (7 and 48%, respectively). Internal N efficiency and remobilization (NHI) were positively correlated at low N supply (0 to 25 kg N ha^{-1}) but not at high N supply (90 to 168 kg N ha^{-1}) across sixteen tropical corn hybrids (Worku et al., 2007). Therefore, hybrids under low N supply relied more on remobilization of previously accumulated N in vegetative tissue to produce grain.

1.1.8.2 Nitrogen Timing

The timing of N application influences the amount of N lost to leaching (Jaynes, 2015), volatilization (Sharpe et al., 1988), and denitrification (Hilton et al., 1994), thus, affects the amount of N the plant can accumulate. Nitrogen fertilizer application timing has had mixed results on IE. One study found higher IE for at-planting application (49 to 79 kg grain yield kg^{-1} N) compared to sidedress application (47 to 71 kg grain yield kg^{-1} N) with greater IE at lower N rates (0, 70, 140, and 210 kg N ha^{-1}) for both application timings (Sainz Rozas et al., 2004). This resulted mainly from a 4 to 10% reduction in plant N content at physiological maturity for at-planting compared to sidedress application, suggesting N loss was responsible for the difference between N timings. Grain yield was reduced by 8% at the low N rate (70 kg N ha^{-1}) but did not differ at the high N rates (140 and 210 kg N ha^{-1}). Another study noted, the application of 168 kg N ha^{-1} during fall, at-planting, or split N application (112 kg N ha^{-1} at planting and 56 kg N ha^{-1} 30 days after planting) resulted in higher IE for fall N application (81 kg grain yield kg^{-1} N) compared to at-planting (76 kg grain yield kg^{-1} N) and split N application (76 kg grain yield kg^{-1} N) (Torbert et al., 2001). Higher IE for fall N application resulted from a greater reduction in plant N content than grain yield.

In contrast to the studies that showed greater IE with less efficient N timings (Sainz Rozas et al., 2004; Torbert et al., 2001), Bigeriego et al. (1979) found that sidedress N application produced higher IE (53 kg grain DM kg^{-1} N) compared to an at-planting application (49 kg grain DM kg^{-1} N) evaluated at three N rates (56, 112, and 168 kg N ha^{-1}) (Bigeriego et al., 1979). The higher IE with sidedress N application was due to higher grain yield and lower plant N content compared to the at-planting application. This occurred due to less N accumulated during vegetative development and more N absorbed during grain fill, which was directly used in grain development for sidedress application compared to at-planting.

The use of nitrification inhibitors (NI) slows the conversion of ammonium to nitrate and may reduce N loss under conditions promoting leaching and denitrification. In a field experiment and meta-analysis, IE was unaffected by NI even though increased grain yield and plant N uptake were observed with use of the NI (Burzaco et al., 2014).

1.1.8.3 Tillage

The utilization of no-till (NT) practices across the U.S. in 2015 accounted for 46% of soybean hectares and 32% of corn hectares (Wade et al., 2015). Conservation practices used on well- and moderately-well drained soils have shown equivalent or higher corn yields over the years (Moschler and Martens, 1975). Some of the benefits with NT are improved water infiltration and utilization, and reduced evaporation and erosion (Hussain et al., 1999; Legg et al., 1979). However, NT practices have higher moisture in the soil's upper surface layers compared to conventional tillage (CT) due to greater amounts of crop residue. Thus, N availability can be reduced due to slower soil warm up and less microbial activity (Rice and Smith, 1984). There is also a greater potential for N loss through denitrification caused by decreased evaporation and removal of water (Burford et al., 1981). These reductions in N availability in NT would likely increase IE. Internal N efficiency was greater in CT (71 kg grain yield kg^{-1} N) at low N supply (67 kg N ha^{-1}) than NT (67 kg grain yield kg^{-1} N) averaged across three years with rainfall over the 30-year average (370 mm). At the higher N rates (202, 336, and 471 kg N ha^{-1}) IE decreased and was greater in NT (71 to 68 kg grain yield kg^{-1} N) than CT (67 to 63 kg grain yield kg^{-1} N) (Moschler and Martens, 1975). The increase in IE at the low N rate in the CT was mainly due to higher grain yield compared to NT. At the higher N rates, IE was improved in the NT due to higher grain yields and lower N uptake than CT. Another experiment also found increased IE in NT (73 kg grain yield kg^{-1}) compared to CT (70 kg grain yield kg^{-1} N) averaged across two years with rainfall higher than the 30-year average (493 mm) (Eghball and Power, 1999). However, this improvement was due to a 5% decrease in total plant N content in NT compared to CT. In the same study, IE was reduced in NT (56 kg grain yield kg^{-1} N) compared to CT (59 kg grain yield kg^{-1} N) during a year with rainfall amounts below the 30-year average. With lower than average rainfall the reduction of IE in NT was mainly caused by a 11% increase in total plant N compared to CT. Greater moisture retention in the upper surface of NT soils during drought conditions allowed for greater N availability and uptake of N, thus reducing IE (Bennett et al., 1973; Doran, 1980). However, a study noted NT had higher IE (51 kg grain yield kg^{-1} N) than CT (48 kg grain yield kg^{-1} N) at the zero N rate when averaged over two years with rainfall below the 30-year average during pollination (103 mm) (Levin et al., 1987). Higher IE in the NT was mainly due to increased grain yield in NT (7,325 kg grain ha^{-1}) compared to CT (6,655 kg grain ha^{-1}). There was no clear difference in IE between NT and CT at higher N rates (45, 90, 135, and 180 kg N ha^{-1}). Greater moisture availability in NT, particularly during pollination, likely decreased crop stress and improved IE.

The availability of N under adequate moisture conditions caused N availability to be greater in CT compared to NT systems due to greater potential loss and immobilization of N in NT (Fox and Bandel, 1986). Therefore, N requirements differed between the two tillage systems with NT requiring more N supplied versus CT (Meisinger et al., 1985). However, other research has shown no differences in N requirements between the two tillage systems and no interaction between tillage and N requirements during growing seasons within the 30-year average rainfall of 397 mm in PA. Therefore, N recommendations should be similar for NT and CT systems (Levin et al., 1987). In addition, N availability was no different between NT and CT across all N treatments (0, 28, 56, 112, and 168 kg N ha^{-1}) indicated by similar ear leaf N concentrations in both tillage systems (~3 g N kg^{-1}) (Triplett et al., 1979). These studies led to the assumption that IE is similar for both tillage systems during growing seasons within the 30-year average rainfall of 397 mm in PA.

1.1.8.4 Plant Density and Row Spacing

Increased plant density has resulted in both increased and decreased IE. One study found differences in IE among three corn plant densities (54,000, 79,000, and 104,000 plants ha^{-1}) varied by hybrid (Ciampitti and Vyn, 2011). All hybrids had the lowest IE (averaged over N rates) at the 54,000 plants ha^{-1}, but maximum IE was produced at the highest density for two hybrids (2M749 = 35 and 2T787 = 45 kg grain DM kg^{-1} N) while the other two hybrids had maximum IE at the intermediate density (2M750 = 39 and 2T780 = 50 kg grain DM kg^{-1} N). This study indicated that increased IE with increased density may be dependent on the hybrid's tolerance to higher densities. In contrast, IE did not differ for two plant densities (60,000 and 90,000 plants ha^{-1}) for one hybrid evaluated at five N rates (0, 1, 2, 3, and 5 kg N 1000^{-1} plants) and the other only differ due to increase number of barren ears at the high population density which reduced IE (Rhoads and Stanley, 1984). However, the whole plant samples were taken 4 weeks after silking to avoid N loss seen at dough (R4) and dent (R5) stages, which was in contrast to Ciampitti and Vyn (2011) who sampled at R6. In addition, IE did not differ for four plant densities (92,600, 104,200, 119,000, and 138,900 plants ha^{-1}) evaluated at four N rates (200, 240, 280 and 320 kg N ha^{-1}) (Fallah and Tadayyon, 2010). However, this study also took whole plant samples between R4 and R5 stages.

One would expect increased plant density to create greater competition for available N, thus, effecting the amount of N taken up by the plant and IE. Under low N supply (0 kg N ha^{-1}) higher plant density (104,000 plants ha^{-1}) decreased N availability, thus, causing early remobilization due to increased competition for N between ear and roots (Boomsma et al., 2009). Another study noted a 5% decrease in the number of ears plant^{-1}, which reduced IE from 63 to 41 kg grain yield kg^{-1} N (Rhoads and Stanley, 1984). Thus, grain yield and sink strength were reduced, which limited the plant's capacity to utilize previously accumulated N to produce grain, thus reducing IE. Plant N content across the three high N rates (2, 3, and 5 kg N 1000^{-1} plants) was 25 to 71 kg N ha^{-1} higher in the high plant density compared to the low plant density, which further suggests sink strength was limited due to an increased number of barren ears at the high density. Higher N supply and plant density may require tolerant hybrids to neutralize the negative effect of high plant density.

Narrower row spacing at a constant plant density increased yield by increasing light interception (Andrade et al., 2002). An increase in yield from narrower rows may lead to improvements in IE due to its effect on the ratio of grain yield and total plant N content. Plant N content at maturity increased linearly or curvilinearly with increased N rate (0, 50, 100, 150, 200, and 250 kg N ha^{-1}) with 38 or 76 cm row spacing, respectively (Cox and Cherney, 2001). Plant N uptake increased through the highest N rate in narrow rows, but not in wider rows. This would negatively affect IE if grain yield were not increased to the same extent. Another study found narrow rows (35 cm), had greater grain yield (8,880 to 13,320 kg grain ha^{-1}) at each N rate (0 and 140 kg N ha^{-1}) compared to wide rows (70 cm; 6,100 to 12,140 kg grain ha^{-1}) evaluated under constant population density (Barbieri et al., 2000). However, in a later study (Barbieri et al., 2008) conducted at a constant plant density (7.30 or 7.65 plants m^{-2} in years 1 or 2 of the study), IE was unaffected by row spacing (70, 52, or 35 cm) and averaged 69 kg grain DM kg^{-1} N across N rates of 0, 90, and 180 kg N ha^{-1}.

1.1.8.5 Soil Texture

The amount of available N mineralized from SOM varies due to differences in soil water content and aeration of different soil textures. Whole soil samples of coarse sand (Lundaard) and two sandy loams (Askov and Ronhave) were separated into clay (<2 um), silt (2-20 um), and sand (20-200 um) fractions to determine the amount of N mineralized from SOM (Christensen and Olesen, 1998). Within each soil, the clay fraction produced higher amounts of mineralized N (504 mg N kg^{-1} clay) compared to the silt fraction (62 mg N kg^{-1} silt). However, clay fractions with higher clay concentration mineralized less N than those with lower concentration of clay. Soil types Lundgaard, Askov, and Ronhave; had 5, 10, and 14% clay and mineralized 747, 441, and 324 mg N kg^{-1} clay, respectively. Soils with higher silt concentration (Lundgaard 7, Askov 13, and

Ronhave 17%) also decreased N mineralized (83, 59, and 44 mg N kg^{-1} silt). For each soil, silt and clay fractions reached maximum mineralization of N with the addition of 4 and 8 t of straw ha^{-1} $year^{-1}$, respectively. The addition of 4 t straw ha^{-1} yr^{-1} increased N mineralized for silt and clay fractions by 27 mg N kg^{-1} silt and 39 mg N kg^{-1} clay, respectively. For each soil, clay fractions increased with the addition of 8 t straw ha^{-1} $year^{-1}$, but silt fractions decreased. With the addition of 12 t straw ha^{-1} $year^{-1}$, N mineralized from clay and silt fractions decreased by 89 mg N kg^{-1} clay and 16 mg N kg^{-1} silt, respectively. Another study found increased clay content decreased N mineralization compared to soils with lower clay content (Hassink, 1994). Thus, suggested immobilization occurred to a greater extent in soil with high clay content.

The soil's ability to store water influences the amount of available N and grain yield produced. A meta-analysis was conducted on 51 field sites grouped into two soil textures (fine-textured and medium- to coarse-textured) due to similar yield response to N between medium and coarse textured soils (Tremblay et al., 2012). Each study had nine N rates where seven treatments (0, 27, 54, 80, 107, 134, and 161) received 36 kg N ha^{-1} of starter. The other two treatments were a control (0 kg N ha^{-1}) and high N treatment (178 kg N ha^{-1}) without starter. About 25 to 35% of the variation in grain yield response to increased N rate was explained by combined factors of soil texture and the distribution of rainfall around sidedress (15 day before to 30 days after sidedress N application). Higher N response was seen in fine and medium to coarse textured soil with better distributed rainfall. However, fine-textured soils had the greatest response to N with improved distribution of rainfall (1,600 to 2,500 kg ha^{-1}) than medium to coarse textured soils (1,600 to 2,000 kg ha^{-1}). The impact of rainfall distribution and soil texture on corn response to N rate may be due to differences in water availability, which impacts the plant's ability to take up available N (Tremblay et al., 2012).

1.1.8.6 Water Availability

The ability to access water throughout the growing season affects the components of IE in the amount of N taken up and grain yield (Bennett et al., 1989). An experiment conducted by Clarke et al. (1990) with two hard red (*Triticum aestivum* L.) and two durum (*Triticum turgidum* L.) wheat hybrids on a Swinton loam soil determined variation in IE was related to water availability. Increased water availability increased IE from 28 to 38 kg grain yield kg^{-1} N averaged across the two years. In corn, IE differed between adequate and deficit water supply and N rates of 116 and 401 kg N ha^{-1} (Bennett et al., 1989). Deficit water supply reduced IE compared to adequate water supply. An interaction between N rate and water supply showed that higher N rates (401 kg N ha^{-1}) combined with deficit water supply further reduced IE from 39 kg grain DM kg^{-1} N (adequate water supply) to 24 kg grain DM kg^{-1} N (deficit conditions). The reduction in IE largely resulted from a 61% grain dry matter reduction (10,382 to 2,553 kg grain ha^{-1}) compared to a 44% decrease in total plant uptake (268 to 105 kg N ha^{-1}). However, water stress during the vegetative period and low N rate (116 kg N ha^{-1}) increased IE from 46 to 54 kg grain DM kg^{-1} N due to reduced total N uptake (131 to 113 kg N ha^{-1}) and similar grain dry matter (6,002 to 6,070 kg grain DM ha^{-1}).

Water availability also affected the rate of N mineralization. Nitrogen mineralization increased with increased water-filled pore space from 20 to 80% (Drury et al., 2003). However, denitrification occurred in treatments where water was in excess (95% water-filled pore space), thus, reducing soil available N. In contrast, severely dry soil released higher amount of soil organic N when the soil was rehydrated causing the stimulation of microbes in the soil. The rehydration of three air-dry soils (one loamy sand and two sandy loams) resulted in microbial population growth, thus, caused the release of N from organic matter sources (Cabrera, 1993).

1.1.9 Summary

Increased N fertilizer cost, decreased corn price, environmental contamination, and a growing population emphasizes the need for increased NUE in crop production systems. One way to improve NUE is to understand how management practices, soil properties, and environmental conditions affect IE. These factors affect the plants' ability to accumulate N and remobilize it to the developing kernels, thus, affecting grain yield and plant N content at maturity. Further understanding of the effects on these factors on IE will help improve yield goal-based N recommendation tools by increasing the accuracy of IE predictions. The first objective of this project was to evaluate IE and its components (grain dry matter (GDM) and plant N content at physiological maturity

(PMN)) response to N rate, application timing, and site productivity (based on historical yield) across three years in IN. The second objective was to determine how the components of IE at the EONR (GDM, PMN, grain N concentration (GNC), stover N concentration (SNC), and stover dry matter (SDM)) correlates with IE at the EONR across a wide range of environments in eight states. The third objective was to assess the variability in IE at EONR and determine soil NO_3-N, soil characteristics, weather, crop reflectance, and plant variables that correlate with IE at the EONR.

CHAPTER 2. FACTORS AFFECTING INTERNAL NITROGEN EFFICIENCY OF CORN

2.1 Introduction

In 2014, corn production in the U.S. accounted for an estimated 6.3 million tons of applied N, which was 48% of the total 13.9 million tons of N applied to U.S. agriculture hectares, thus, making it one of the largest inputs in a farmer's operation (USDA-ERS, 2018). Nitrogen fertilizer is also one of the hardest inputs to due to its variation in availability and plant uptake across soil and climate conditions (Tremblay et al., 2012). This ultimately affects the economic optimum N rate (EONR) across a given field (Scharf et al., 2005) and the year to year field average (Nafziger et al., 2004). These variations lead to the under and over application of N fertilizer causing reduced profit and water quality.

Historically, yield goal-based N recommendation tools have been utilized to predict optimum N rates for a given field (Morris et al., 2018) despite a poor relationship of yield goal with EONR (Sawyer et al., 2006). This approach was based on a target whole plant N content derived from yield goal and a plant N content per kg of grain produced. This idea was originally proposed by Stanford (1966) who derived from field experiments a value of ~0.02 kg N kg^{-1} grain yield that appeared unaffected by environmental differences or management practices. This value is the inverse of IE and is equivalent to ~47 kg grain yield kg^{-1} N. Since the work of Stanford (1966, 1973) other research has shown this value to vary (Bennett et al., 1989; Ciampitti and Vyn, 2012; Moll et al., 1982; Woli et al., 2016). Variation in the N requirement per unit of grain yield may be one of the reasons for the poor accuracy of optimum N rate predictions in yield goal-based N recommendation tools.

Many N response studies conducted over the last four decades showed that IE decreased with increased N supply (Barbieri et al., 2008; Eghball and Maranville, 1991; Kamprath et al., 1982; Moll et al., 1982; Muchow, 1998). Griffin (2008) noted crop management, soil characteristics, and environmental factors, such as temperature, soil moisture and texture, to influence the amount of N available. As a result, these factors may contribute to variation in IE. Internal N efficiency varies among hybrids and genotypes (Ciampitti and Vyn, 2012; Kamprath et al., 1982; Moll et al., 1982; Woli et al., 2016), but few have investigated IE over a wide range of growing conditions. Knowledge of soil and environmental factor effects on IE will help improve the understanding of N utilized by the plant and improve the accuracy of yield-goal based N recommendation tools for their use across different growing conditions. One objective was to assess IE and its components (grain dry matter (GDM) and plant N content at physiological maturity (PMN) response to N rate, productivity site, and/or timing across three years in IN. The second objective was to evaluate IE response to N rate and determine IE at the EONR (IE_E) relationship with its components (GDM, PMN, grain N concentration (GNC), stover N concentration (SNC), and stover dry matter (SDM)) at EONR. The third objective of this project was to evaluate the relationship between weather, soil characteristics, soil NO_3-N, crop reflectance, and plant variables with IE_E across a wide range of environmental conditions. These objectives helped to evaluate the amount of variation that IE contributes to yield goal-based N recommendations and if there are factors at can predict IE.

2.2 Materials and Methods

2.2.1 Experiment Design

A partnership of eight land-grant universities (Iowa State University, University of Illinois at Urbana-Champaign, Purdue University, University of Minnesota, University of Missouri, North Dakota State University, University of Nebraska-Lincoln, and University of Wisconsin-Madison) with DuPont Pioneer (DuPont Pioneer, Johnstown, IA) conducted 49 small-plot N response trials in 2014-2016. Protocol and methods were mostly the same across all site-years. Trials were established on producer or public agriculture research stations. Each year, two contrasting soil types in each state (three sites for Missouri in 2016) were selected based on historical yield data showing different levels of productivity. In subsequent years, different plot areas were selected. The scope of the project allowed a wide range of soil types to be evaluated (Table 1). There were six sites that ranged from loamy sand to sandy loam while the remaining sites were located on soils with loam (7), silt loam (25), silty clay loam (5), clay loam (5), and clay (1) textures.

Variation in growing season length occurred as a result of wide geography area (~ 1.35 million km^2) covered by this project. DuPont Pioneer hybrids used across the 49 site-years ranged from 89 to 114 days in relative maturity. This wide range was needed to compensate for differences in growing season length and reduce the risk of frost injury. Hybrids were also selected for traits to optimize grain yield potential. Most sites were planted at a seeding rate of 86,450 plants ha^{-1}, however, seeding rate was adjusted at some sites based on soil productivity (Table 2). The average population at harvest across all 49 site-years was 80,640 plants ha^{-1}. Planting dates across the years ranged from April 6 to May 24. The majority of the sites were located on fields previously planted with soybean (43) with the remaining sites previously planted with corn (5) or sunflower (1). Eight of 49 site-years were tile drained fields. There were eight irrigated site-years. Tillage preceded planting at 34 site-years; 15 were no-till. Descriptions of management practices and dates of field activities are presented in Tables 2 and 3, respectively.

Plot dimensions varied from 12.2 to 18.2 m long and 3.05 to 9.1 m wide due to differences in planter and harvest equipment. Row width was 76 cm for all states except North Dakota, which was 56 cm. Grain yield was estimated from a minimum harvest area of 18.6 m^2.

Treatments were eight N rates applied at planting (0 to 315 kg N ha^{-1} in 45 kg ha^{-1} increments), six N rates split, with 45 kg N ha^{-1} at planting and additional fertilizer (45 to 270 kg N ha^{-1} in 45 kg ha^{-1} increments) applied at the V9±1 corn growth stage, and two N rates split with 90 kg N ha^{-1} at planting and a V9±1 corn growth stage application of 90 or 180 kg N ha^{-1}. At the majority of sites, ‘at-planting’ applications were made a few days prior to planting or within seven days after planting. At Nebraska in 2016, low and high sites, ‘at-planting’ fertilizer was applied at 24 and 29 days prior to planting, respectively. In North Dakota, the split N application was applied at V5 and V8 in 2015 and 2016. Ammonium nitrate (El Dorado Chemical Company, Rockwell, TX, USA) was broadcast uniformly on the soil surface at both application timings using a shoulder spreader (at-planting) and by hand (at V9±1 V-stage). Treatments were arranged in a randomized complete block and replicated four times.

Additional N was applied at several site-years. Starter fertilizer was applied at planting as 10-34-0 for four of six Nebraska site-years. In 2016, the entire plot area at North Dakota high productivity site received an additional 45 kg N ha^{-1} as a granular mixture of urea (84 kg N ha^{-1}) and ammonium sulfate (28 kg N ha^{-1}) due to a custom application error. The 2014 IN low site received an additional 23 kg N ha^{-1} as a broadcast application of MAP (11-52-0) in early December of 2013. Additional N (above 11 kg N ha^{-1}) supplied in irrigation water was estimated for each irrigated site. Pest damage from corn rootworm and Northern Corn Leaf Blight were seen in Illinois (2014) and Indiana (2015), respectively. Additional fertilizer and pesticide application are listed in Table 4.

2.2.2 Routine Soil Sampling

Routine soil samples were collected in the spring at each site. Three 0-15 cm soil cores were taken from each replication and combined to form one composite sample for each replication. Each university selected local soil test laboratories to determine the level of P, K, pH, and percent organic matter. Routine soil analysis data are presented in Table 5.

2.2.3 Site Characterization

The University of Missouri and USDA ARS conducted site characterization for each site one to four weeks prior to planting. A Veris 3100 instrument (Veris Technologies, Inc., Salina, KS, USA) was used to gather data needed to create a soil electrical conductivity map which identified soil variability and dictated where soil samples were taken (Sudduth et al., 2005). Estimates of EC were made for shallow and deep soil reading while the equipment was run at 1.3 m s^{-1} on 4.6 m spaced transects, which allowed one observation to be recorded every second. There were four to six transects run perpendicular to the original pass at 9 m spacing. For each site a minimum of 800 total observations were recorded. Soil electrical conductivity maps were created from these observations by reorganizing them into ten categories based on the range of the data. Once soil variability was identified in each replication, one 1.2 m soil core was taken from each of the four replications using a hydraulic sampler with a 5.1 cm diameter tube and a 3.8-4.0 cm diameter bit. Descriptions of the soil cores were recorded by horizon along with their depths. Plastic bags were used to keep each horizon separate. Soil samples of each horizon were placed into coolers filled with ice and transported to University of Missouri for processing. Samples were laid out to air dry before they were ground through a 2 mm sieve. Soil analysis was conducted by University of Missouri's Soil Heath Assessment Center to determine the physical and chemical properties of each sample. This allowed for soil particle size, cation exchange capacity (CEC), total organic carbon (TOC), total carbon (TC), total inorganic carbon (TIC), total N, pH (salt and water), and organic matter (OM) to be determined. After OM was removed, the pipette method was used to determine soil particle size (Soil Survey Staff, 2014). Cation exchange capacity was determined from ammonium acetate buffered to pH 7.00 and the steam distillation method. A LECO C-144 Carbon Determinator (LECO Corporation, Saint Joseph, MI, USA) was utilized to perform dry combustion method on a ~0.5 g soil sample for TOC and TC. Total organic carbon was determined from an early peak in loss. The same sample was used to determine TC, which accounted for additional loss up to 927 ºC. A LECO FP-F528 Nitrogen/Protein Determinator (LECO Corporation, Saint Joseph, MI, USA) was used in the dry combustion method to determine total N. A 1:1 soil to water and soil to salt (1 N KCl) ratio was utilized to determined pH. Organic matter was determined by the loss-on-ignition method using a Thermogravimetric Analyzer (LECO Corporation, Saint Joseph, MI, USA) (Nelson and Sommers, 1996). Bulk density (BD) was determined for each soil core by obtaining their weight before oven drying at 105ºC and after they reached a constant weight. This allowed BD to be calculated by dividing dry weight by the volume of soil, which was determined from horizon length and the surface area of the soil core bit used to extract the samples. Saxton and Rawls (2006) formula was utilized to calculate gravimetric water content (WC), which required sand, clay, organic matter, and bulk density information to determine soil moisture at permanent wilting point and field capacity. These moisture measurements were then used to calculate plant available water content by subtracting permanent wilting point from field capacity. The Soil Survey Geographic database (SSURGO) was used to gather plant available water content (PAWC) at the 0-30, 30-60, and 60-90 cm depth and averaged over each depth (0-90 cm depth).

The weighted mean of each site characterization variable was taken based on horizon depth. A maximum depth was set at 95 cm based on the number of locations with soil profiles extending to that depth. The following calculation was used for each site characterization variable:

Weighted Mean = Site Variable * BD * (Σ Horizon Depths to 95 cm) / BD * (Σ Horizon Depths to 95 cm)

2.2.4 Soil Nitrate Sampling

Soil nitrate samples were collected from each of the 49 site-years at four different times during each growing season (pre-plant (PPNT), pre-sidedress (PSNT, V5±1 V-stage), tasseling (VTNT), and post-harvest (PHNT)) (Table 6). Timing of soil nitrate sampling was two to four weeks before planting, tasseling (VT), and within four weeks after harvest for PPNT, PSNT, VTNT, and PHNT, respectively. At each sampling time 1.9 cm diameter soil cores (except post-harvest) were separated into 30-cm increments. At PPNT ten soil cores were taken to a depth of 90 cm with a hand probe from each replication and combined into one composite sample for each replication block. There was only one observation taken at 60-90 cm depth in 2016 at the Wisconsin low site due to a constricting rock layer below 30 cm depth. North Dakota took PPNT samples from 0-15, 15-60, and 60-90 cm in 2016. At PSNT, six soil cores were taken to a depth of 60 cm from each N rate applied at-planting including the 0 N rate, which were combined into one composite sample for each plot and depth increment. Soil samples were only taken from a depth of 0-30 cm in 2014 at North Dakota high and Nebraska low site, along with Nebraska high sites in 2016. At VTNT three soil cores were taken to a depth of 60 cm from 0-0, 90-0, 180-0, and 270-0 at planting N rates and 40-40, 40-120, 40-200, and 80-80 split N rates. The three soil cores were combined into one composite sample for each plot and depth increment. There were no VTNT soil samples taken at either productivity sites in IA and ND in 2014 and 2015, respectively. Soil samples were only pulled at the 0-30 cm depth in 2014 at Indiana (high and low) and Nebraska (low) sites, and again in both Nebraska productivity sites in 2015 and 2016. University of Missouri and USDA-ARS took post-harvest nitrate samples within four weeks after the harvest date. A hydraulic sampler (Giddings Machine Company Inc., Windsor, CO, USA) with a

4.13 cm diameter core and 3.0 cm diameter tip was utilized to pull three soil cores from each plot to a maximum depth of 90 cm. The Wisconsin low site in 2016 PHNT soil samples were only pulled from a depth of 60 cm due to a constricting rock layer, which also caused one to three missing observations in some N rates at 60 cm depth. The N rates sampled and the number of subsamples taken at each sampling time are listed in Table 6. Samples from PPNT, PSNT, VTNT, and PHNT were kept cool during their transport back to university campuses where they were air-dry or oven dried (≤ 32ºC) within 12 h of sampling. Samples were frozen or refrigerated if they were unable to be air dried within the 12 h time frame. A flail type grinder was used to ground the dried soil samples through a 2 mm sieve then thoroughly mixed before sending to Agvise Laboratories (Northwood, ND, USA) for soil nitrate-N analysis using the Cadmium Reduction method (Gelderman and Beegle, 1998).

2.2.5 Reflectance Measurement

A RapidSCAN CS-45 (RS) Handheld Crop Sensor (Holland Scientific, Lincoln, NE) was utilized to measure crop reflectance data prior to the sidedress N application (between V8 to V10, except for 2015 and 2016 North Dakota sites where sensing took place between V5 and V8) (Table 3). In 2014, the North Dakota sites used a Crop Circle-430 (Holland Scientific, Lincoln, NE) with wavelengths scaled differently than the RS, which eliminated it from comparison across site-years. Manufacturer guidelines were followed during system setup. Each plot was scanned by holding the RS approximately 60 cm above each grain yield row with a walking pace approximately 4 km hr^{-1}. An average of 200 to 300 readings, along with three wavelengths of light (red 670 nm, VIS; red edge 720 nm, RE; near-infrared 780 nm, NIR), were collected for each plot.

The following calculations were generated from crop reflectance data:

$$NDVI = (NIR – R) / (NIR + R)$$

$$NDRE = (NIR – RE) / (NIR + RE)$$

Sufficiency Indices:

$$NDVI_{0}225 \text{ or } 270 = NDVI_{0N} / NDVI_{225 \text{ or } 270N}$$

$$NDVI_{45}225 \text{ or } 270 = NDVI_{45N} / NDVI_{225 \text{ or } 270N}$$

$NDRE_0225 \text{ or } 270 = NDRE_{0N} / NDRE_{225 \text{ or } 270N}$

$NDRE_{45}225 \text{ or } 270 = NDRE_{45N} / NDRE_{225 \text{ or } 270 N}$

Sufficiency indices ($NDVI_0225$, $NDVI_{45}225$, $NDVI_0270$, $NDVI_{45}270$, $NDRE_0225$, $NDRE_{45}225$, $NDRE_0270$, and $NDRE_{45}270$) were calculated using the NDVI or NDRE of the 0 or 45 kg N ha^{-1} treatments divided by the NDVI or NDRE of the 225 or 270 kg N ha^{-1} treatments.

Simple Ratio Index:

$SI_{R0 \text{ or } 45} = R_{0 \text{ or } 45N} / NIR_{0 \text{ or } 45N}$

$SI_{RE0 \text{ or } 45} = RE_{0 \text{ or } 45N} / NIR_{0 \text{ or } 45N}$

Simple ratio indices (SI_{RE0}, SI_{RE45}, SI_{R0}, and SI_{R45}) were calculated using the red or red edge reflectance of the 0 or 45 kg N ha^{-1} divided by near infrared of the 0 or 45 kg N ha^{-1}.

2.2.6 Tissue and Grain Sampling

Six consecutive plant were cut at ground level at VT and at physiological maturity (R6) from non-grain yield and grain yield rows, respectively. Biomass sampling dates ranged from June 28 to July 31 and August 21 to October 10 for VT and R6, respectively (Table 3). There were no VT biomass samples taken in N rates 45-90, 45-180, and 45-270 kg N ha^{-1} at Nebraska high and low sites in 2015. Biomass samples were not collected at VT for Wisconsin and Nebraska low sites in 2016. At R6, grain and cob were separated from above-ground biomass before processing. There were no grain or cob samples taken from North Dakota productivity sites in 2015.The total wet weight of all six plants was obtained shortly after cutting. Plant material at VT and R6 were either dried as whole plant or chopped and subsampled before drying at 60 to 70°C. A vegetative subsample was taken for moisture determination for each plot. Dry weight for grain, cob, and stover components were recorded once samples reached a constant weight. Ground subsamples for both plant tissue (1 mm sieve) and grain were shipped to Agvise Laboratories for determination of total N content. The dry combustion method using Elementar Rapid N Cube Nitrogen analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany) was used to determine plant and grain N content (Bremner, 1996). Cob N was estimated to contain 4.8% of the total plant N ((grain N + leaves N + stalk N) * 0.048). In 2016, Nebraska calculated N and dry matter content for vegetative, cob, and whole plant from harvest index and cob harvest index. Grain yield was hand harvested or by plot combine on a minimum of 18.6 m^2 of plot area. The grain yield from the six R6 plant samples were included in the final yield calculation. In 2016, grain yield was adjusted to compensate for grain lost due to a tear in the plot combine screen which occurred at both IN productivity sites. Grain yield was adjusted to 0 g kg^{-1} moisture.

The following calculations were completed using tissue and grain data:

Cob N uptake (kg ha^{-1}) = (Grain N + Stover N) * 0.048

Net Change in Stover N (kg ha^{-1}) = R6 Stover N – VT Stover N

Internal N Efficiency (IE) (kg kg^{-1}) = Grain DM / (Stover N + Grain N + Cob N)

2.2.7 Weather and Climate Data

A HOBO U30 Automatic Weather Station (Onset Computer Corporation, Bourne, MA) was placed near each trial site, except in two locations. At the 2014 North Dakota high site, a North Dakota Agricultural Weather Network weather station located 5.6 km from the field site was used to collect weather data. For the 2016 Missouri low site the University of Missouri's Bradford research station was utilized to collect weather data located 1.9 km from the field. All weather stations were checked on a routine basic to insure proper function and to clear debris from the rain gauge when observed. Hobo weather stations collected precipitation, solar radiation, maximum and minimum temperature data every 15 min with a TX300 data logger (Onset Computer Corporation, Bourne, MA). Precipitation data was measured using a tipping bucket rain gauge. A solar radiation guard was used to measure temperature and relative humidity. The raw data collected from the weather station (total daily precipitation, maximum and minimum temperature, and solar radiation) was summarized by DuPont Pioneer weather data interpolation procedures and Multi-Radar/Multi-Sensor rainfall data. Data was corrected for any outliers or missing data values by interpolated temperature or MRMS rainfall estimates. Weather stations located at the IN sites (low and high) were located approximately 0.5 miles away from each other, however, rainfall amounts were large different between locations. To adjust for these differences each weather station (low and high) were compared to between each other and three other weather stations located near the two IN sites (automated Purdue weather station and manual read NOAA station located within 200 yards, and Valparaiso airport station (5 miles away)). There were 42, 108, and 20 daily rainfall amounts replaced in 2014, 2015, and 2016, respectively. These changes resulted in only a one inch difference between high and low productivity sites and NOAA weather stations. A summary of total rainfall during the growing season and at different growth stages is listed in Table 7.

Precipitation (mm) was utilized to calculate Abundant and Well-Distributed Rainfall (AWDR; Tremblay et al., 2012) (Table 8) in conjunction with the Shannon Diversity Index (measure of evenness; SDI). These calculations were completed with the following equations:

$$SDI = [- \sum pi * \ln(pi)] / \ln (n)$$

The Shannon Diversity Index consists of pi = daily precipitation divided by the total rainfall within a specific time frame, n = number of days within a specific time frame. A value of one was inserted for observations where no rainfall was recorded, thus, causing the log of one to equal zero.

$$AWDR = SDI * \text{Total Precipitation}$$

Precipitation was recorded in mm. These equations were used to analyze weather data obtained from two weeks before and/or after N applied at-planting and split-applied N, throughout the vegetative growth period, two weeks before and after tasseling, during the grain fill period, and from planting to physiological maturity.

2.2.8 Data Analysis

2.2.8.1 Response to Nitrogen Rate, Timing, and Productivity site in Indiana

Statistical analysis was performed in SAS 9.3 (SAS Institute Inc., Cary, NC). Years and state locations were analyzed individually. Simple statistics were conducted on plant, crop reflectance, soil, and weather variables to determine the number of observations, mean, standard deviation, minimum, and maximum values. Besides the missing data mentioned previously, a few sites were missing observations from one or two plots, thus, making the data slightly unbalanced. Several environments had three or four N rates with standard deviation equal to zero for cob N and grain N concentration, thus, inflated F-values. In the ANOVA, these values were set to missing. A transformation was considered if the range of the means (averaged across N rates) divided by grand mean was greater than 0.5, thus, a Box-Cox Regression was carried out to determine log or square root transformation. However, no variable qualified for a transformation.

In IN over the three years, an ANOVA generated from PROC GLM was used to obtain sum of square and mean square for each productivity sites. An F-test was used to determine if productivity sites error variances were homogeneous, thus, high productivity sites were divided by low productivity sites error mean square to determine the F-value for each variable. If the F-value was less than one, then the low productivity site error mean square was divided by high productivity site error mean square. The F-value was used to determine if the error variances were homogenous ($\alpha \geq 0.10$). When homogeneous productivity sites within a state and year were combined for analysis. Variables with F-values < 0.10 were considered heterogeneous and each site within a state and year was analyzed separately.

In all three years in IN, grain dry matter (GDM), plant N content at physiological maturity (PMN), and internal N efficiency (IE) were tested for N treatment effects using mixed analysis of variance conducted with PROC MIXED if productivity sites were heterogeneous ($\alpha \leq 0.10$). Least square means (LSMeans) were generated for each of the three variables to fill in missing gaps in the data set. All sixteen N rates were compared with a t-test to determine if there were differences among N rates. Variables LSMeans with differences between N rates were compared with the mean least significant difference (LSD) value, which also allowed variables with unbalanced data to be compared. Nitrogen rate effect within a productivity site was determined using a type III test of fixed effect where an F-value was calculated for each heterogeneous variable. Significant variables were run through a mean separation test within a productivity site. For each productivity site (low and high), a two-way interaction was tested for each of the three variables linear and/or quadratic response to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) with timing (all 'at-planting' or 'split' 45 kg N ha^{-1} at planting remainder applied V9±1 V-stage). If the linear and quadratic response to N rate were dependent on timing within a variable and a site-year, then the interaction between the quadratic response to N rate and time was used. Variables with non-significant interaction were then tested for linear and/or quadratic N rate and timing main effect. An

F-test was used to determine the significance of the main effect and interaction. If a significant linear and quadratic response to N rate occurred within a variable and site-year, then the quadratic response to N rate was used instead of the linear response.

Heterogeneous variables were dropped when homogeneous variables were compared. In all three years in IN, a general linear model was used to pool the residual error of variables with significant homogeneity error variance in an attempt to add variation not explained by the model into the residual error, thus helping to increase the residual degrees of freedom. However, the majority of the three variables' residual error were not able to be pooled, so PROC MIXED was used to conduct the ANOVA. Homogenous variables were tested for differences and interactions between N rates for each productivity site and main effect using a t-test. The t-value was calculated from estimated values divided by standard error, which included a block productivity site component; significant was determined at $\alpha \leq 0.10$. A type III fixed effect was used to test for significant difference between N rates for the main effect and interaction between productivity sites using an f-test. Least significant difference mean values were used similar as heterogeneous variables. Significant LSMeans for main effect or interaction between productivity sites for N rate were utilized for a separation test for each variable. A three-way interaction was conducted between variables linear and/or quadratic response to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) with timing (all 'at-planting' or 'split' 45 kg N ha^{-1} at planting remainder applied V9±1 V-stage) and productivity site (low and high). The interactions between linear or quadratic response to N rate with timing and/or productivity site within a variable and a site-year ($\alpha \leq 0.10$) were selected based on quadratic N rate*Timing*Productivity site > linear N rate*Timing*Productivity site > quadratic N rate*Timing or Productivity site > linear N rate*Timing or Productivity site. An interaction between timing and productivity site was also conducted. Variables with non-significant interactions there then tested for the linear and/or quadratic N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1}), timing (all 'at-planting' or 'split' 45 kg N ha^{-1} at planting remainder applied V9±1 V-stage), and productivity site (low and high) main effects. If the main effect for linear and quadratic response to N rate were significant then the quadratic response to N rate was used instead of the linear response to N rate.

2.2.8.2 Response to Nitrogen Rate and Timing across Eight States Over Three Years

Across eight states over three years, GDM response to N rate was determined using PROC NLIN to produce a quadratic-plateau regression for each productivity site (low and high: based on historical yield data) and N application timing (at-planting and split), except for 2016 Wisconsin (WI) high site (at-planting) used a quadratic response created from PROC REG. Regression for both application timings used N rates 0 and 45 kg N ha^{-1} to insure regressions were weighted equally, while N rates 90-90 and 90-180 kg N ha^{-1} were dropped from both regressions. Initial parameters for 92 of 97 quadratic-plateau models were set at a range of 12095.0 to 1536.2 (a), 111.9 to 16.0 (bx), and 0 to -1.0598 (c^2). The five other quadratic-plateau models initial parameters were set differently for 2015 Minnesota (MN) high split (5,369.5 (a), 34.8 (bx), and -0.1047 (c^2)), 2014 Nebraska (NE) high at-planting (11,551.3 (a), 42.7 (bx), and -0.2202 (c^2)), 2016 WI high split (10,625.0 (a), 26.8 (bx), and -0.0840 (c^2)) and low at-planting and split (7,899.7 (a), 44.44 (bx), -0.2996 (c^2)). Regression parameters were tested for significance using a t-value of ≤ 0.10. Confidence intervals were calculated at 90% and 95%, thus, regression models were determined significant at $\alpha \leq 0.10$. The economic optimum N rate (EONR) was calculated based on a \$0.88 kg^{-1} N to \$0.157 kg^{-1} grain ratio. Agronomic optimum N rate (AONR) and EONR ranged from 0 to 315 kg ha^{-1}, however, optimum N rates were set to not exceed maximum N rate used in the study. The optimum N rates were set to zero, and GDM was reported as the mean GDM of all the N rates where the quadratic-plateau response was non-significant (2015 WI high, 2016 North Dakota (ND) high and low). The 2016 WI high site (at-planting) optimum N rates were determined from a quadratic model. Grain dry matter at both optimum N rates were determined from the quadratic or quadratic-plateau function for each application timing. All regressions parameters, along with plateau and predicted values, were compared between applications timings using a significant level at $\alpha \leq 0.10$.

Across eight states over three years, a quadratic and linear regressions were fitted to both application timings for IE, stover dry matter (SDM), stover (SNC) and grain N concentration (GNC) using PROC REG. Stover dry matter was also tested for a quadratic-plateau regression with initial parameters set a 549 to 9429 (a), 43.3 to 9.5 (bx), and -0.1073 to -0.0192 (c^2). Both application timings utilized N rates 0 and 45 kg N ha^{-1}

in their data set to allow regressions to be weighted properly, while N rates 90-90 and 90-180 kg N ha^{-1} were dropped from each regression. Confidence intervals were calculated at 90 and 95%, thus regression models and their parameters were considered significant at $\alpha \leq 0.10$. For SDM, non-significant quadratic-plateau were then tested for quadratic regression. For variables, the quadratic regression was changed to linear if the slope and/or c^2 parameters were non-significant. The mean across N rates was taken for variables with non-significant linear regression model or slope. Regression equations were used to estimate the value of each variable at the EONR. Regression parameters were compared between N application timing (at-planting and split), along with each variable at the EONR.

Across eight states over three years, Pearson correlation (PROC CORR) was used to evaluate plant, soil, weather, crop reflectance, and components of IE at EONR mutual relationship with IE_E and between each type of variable. Correlations were conducted with at-planting and split application values, even though some values were not significantly different. This allowed the correlation to be weighted properly. Confidence and predictive intervals were calculated at 95% for each variable regressed against IE_E, thus, regressions were considered significant at a *p*-value of ≤ 0.10. Correlation coefficients (r) strength were categorized based on ranges from $0.20 \leq r < 0.50$ (weak), $0.50 \leq r < 0.70$ (moderate), and $r \geq 0.70$ (strong).

Multiple regression models, performed with PROC REG, were constructed using plant, soil, weather, and crop reflectance variables to predict IE_E and N recommendation. Forward selection procedure was used to input significant variables into the model. To avoid multicollinearity between variables inflation factor were used along with two steps. Step 1: Variables with an inflation factors higher than ten and/or F-probability greater than 0.10 were removed from the model. Step 2: When inflation factors were greater than or equal to four and less than ten, correlations between the variables in the model with an $r \geq 0.60$ were removed based on scientific principle and practical use. After one variable was removed, the model was rerun and steps 1 and/or 2 were repeated until none of the variables in the model meet the criteria for either step. Multiple models were constructed during different periods of the season (at-planting, sidedress, late N application (after V10), and rescue N application (at VT)) to predict IE_E and N recommendation.

2.3 Results

2.3.1 Response to Nitrogen Rate, Timing, and Productivity site in Indiana

2.3.1.1 Grain Dry Matter

In 2014 and 2015, each pair of productivity sites (low and high) in IN had homogenous error for GDM in a given year, thus, were run as a combined analysis for GDM response to N rates ranging from 90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments (Table 9). There was no interaction between N rate, productivity site, and/or timing in 2014 IN sites ($p > 0.10$, Table 9). In 2014, GDM increased quadratically to increasing N rate from 10,212 to 11,749 kg ha^{-1} ($p \leq 0.10$, Fig. 1). Nitrogen split-applied resulted in higher GDM (11,574 kg ha^{-1}) than N applied at-planting (11,163 kg ha^{-1}) in 2014 ($p \leq 0.10$, Fig. 2).

In 2015 IN, the response to N rate differed by site and timing ($p \leq 0.10$, Table 9, Fig. 3), with greater GDM at the low productivity site (9,666 to 12,917 kg ha^{-1}) than at the historically high productivity site (7,179 to 9,090 kg ha^{-1}) at all N rates, and greater differences at higher N rates. At the low productivity site, GDM did not differ with application timing [AP (9,666 to 12,512 kg ha^{-1}) and S (10,324 to 12,917 kg ha^{-1})]. At the high productivity site, GDM was greater with N split-applied (7,904 to 9,090 kg ha^{-1}) than with N applied at-planting (7,179 to 6,572 kg ha^{-1}) where GDM declined gradually with higher at-planting N rates. Lower GDM at the high productivity site, particularly with at-planting N, coincided with greater incidence of Northern Corn Leaf Blight (NCLB; causal agent *Exserohilum turcicum*). Average loss of leaf area (ear leaf plus one leaf above) was higher for N applied at-planting (69% loss of leaf area) than split-applied (58% loss of leaf area), especially as N rate increased (Fig. 4). At the low productivity site, loss of leaf area from NCLB was unaffected by timing or N rate and averaged 12% ± 9.

In 2016 IN, the two productivity sites had non-homogenous error, thus were analyzed separately (Table 9). At the low productivity site, GDM increased linearly to increasing N rate (12,372 to 13,198 kg ha^{-1}) (Fig. 5). In contrast, the high productivity site GDM increased quadratically (11,363 to 12,701 kg ha^{-1}) to increasing N rate (Fig. 6).

2.3.1.2 Plant Nitrogen Content at Physiological Maturity

In 2014 and 2015 the two productivity sites in IN had non-homogenous error, thus, were analyzed separately (Table 9). In 2014 at the low and high productivity sites, PMN increased quadratically [L (180 to 276 kg ha^{-1}) and H (172 to 245 kg ha^{-1})] to increasing N rates ranging from 90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments ($p \leq 0.10$, Fig 7A and B). The low productivity site with N split-applied had higher PMN (248 kg ha^{-1}) compared to with N applied at-planting (238 kg ha^{-1}) ($p \leq 0.10$, Fig. 8). At the high productivity site, there was no difference in PMN between N application timings ($p >$ 0.10).

In 2015, PMN increased quadratically in response to N rate at the low productivity site (158 to 264 kg ha^{-1}) ($p \leq 0.10$, Fig. 9) and linearly at the high productivity site (123 to 219 kg ha^{-1}) ($p \leq 0.10$, Fig. 10). Split-applied N in the high productivity site resulted in higher PMN (193 kg ha^{-1}) than N applied at-planting (158 kg ha^{-1}) ($p \leq 0.10$, Fig. 11). Lower PMN at the high productivity site with N applied at-planting coincided with greater incidence of NCLB (AP = 69% vs. S = 58% loss of leaf area), especially with greater N rates (Fig. 4). The low productivity site had an average of 12% ± 9 leaf area loss due to NCLB and was unaffected by timing and N rate ($p > 0.10$).

In 2016, the two productivity sites in IN had homogenous error for PMN, thus were analyzed as a combined analysis for PMN response to N rates ranging from 90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments ($p \leq 0.10$, Table 9). In 2016, PMN response to N rate was dependent on productivity site and timing ($p \leq 0.10$, Table 9). At the high productivity site, increasing N rate increased PMN for both timings, and differences between timings were similar across the range of N rates [AP (175 to 251 kg ha^{-1}) and S (164 to 243 kg ha^{-1})] ($p \leq 0.10$, Fig. 12). At the low productivity site with N applied at-planting, PMN increased with higher N rate similar to the response at the high productivity site [AP (206 to 272 kg ha^{-1}) and S (227 to 251 kg ha^{-1})]. However, spilt-applied N did not increase PMN above the 90 kg N ha^{-1} treatment (253 kg ha^{-1}).

2.3.1.3 Internal Nitrogen Efficiency

In 2014 and 2016, productivity sites in IN had non-homogenous error, thus, were analyzed separately (Table 9). In 2014 at the low and high productivity sites, IE declined with increasing N rates in a quadratic fashion [L [58 to 44 kg GDM kg^{-1} N] and H [59 to 47 kg GDM kg^{-1} N]) ($p \leq 0.10$, Fig. 13A and B, respectively).

In 2015, productivity sites in IN had homogenous error, thus, were run as a combined analysis for IE response to N rates ranging from 90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments (Table 9). Internal N efficiency decreased with increasing N rate for all combinations of productivity and N timings. The exact IE response to N rate was dependent on productivity site and timing ($p \leq 0.10$, Fig. 14). At the low productivity site, split application at the intermediate N rates (180 and 225 kg N ha^{-1}) resulted in higher IE (54 kg GDM kg^{-1} N, respectively) than N applied at-planting (50 kg GDM kg^{-1} N). In contrast, at the high productivity site, N applied at-planting at intermediate N rates resulted in higher IE (48 to 46 kg GDM kg^{-1} N) than split-applied N (45 to 40 kg GDM kg^{-1} N). The low productivity site had higher IE at the intermediate N rates than the high productivity site, and differences increased at higher N rates. The differences between productivity sites and timing in the high productivity site coincided with greater incidence of NCLB. The average loss of leaf area in the high productivity site was related to N rate and timing (AP = 69% vs. S = 58% loss of leaf area). The average loss of leaf area in the low productivity site was 12% ± 9 and was unaffected by timing.

In 2016 at the low productivity site, IE response to N rate was dependent on timing ($p \leq 0.10$). Internal N efficiency decreased linearly with increasing N rate for N applied at-planting (60 to 49 kg GDM kg^{-1} N) (Fig. 15). Internal N efficiency was not responsive to N rate with split-applied N (55 to 53 kg GDM kg^{-1} N). At the high productivity site, IE (averaged over N application timing) declined linearly with increased N rate (68 to 52 kg GDM kg^{-1} N) ($p \leq 0.10$, Fig. 16). In the same productivity site, IE (averaged over N rates within an application timing) was higher with split-applied N (60 kg GDM kg^{-1} N) than N applied at-planting (55 kg GDM kg^{-1} N) ($p \leq 0.10$, Table 9, Fig. 17).

2.3.2 Effectors and Predictors of Internal Nitrogen Efficiency at the Economic Optimal Nitrogen Rate across the Forty-Nine Site-Years

2.3.2.1 Internal N Efficiency at the Economic Optimal Nitrogen Rate

When examined for each application timing at each site year, linear and quadratic functions explained IE response to N rate (0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) at 61 and 29, respectively, of 94 site-years and application timings ($p \leq 0.10$, Table 10, 2015 ND data missing). Internal N efficiency decreased with increased N rate for 84 of 94 site-years and N application timings, while six site-years and N application timings increased with increasing N rate ($p \leq 0.10$). At four site-years, IE did not respond to N rate ($p > 0.10$).

Estimated values of IE at the economic optimal N rate (IE_E) ranged from 38 to 73 kg GDM kg^{-1} N with an average of 54 kg GDM kg^{-1} N (Table 10). The economic optimal N rate (EONR) ranged from 0 to 315 kg N ha^{-1} with an average of 167 kg N ha^{-1} and was not related to IE_E ($p > 0.10$, Table 10). There were no differences between timings within a site-year at 24 of 47 site-years ($p > 0.10$). Differences between N application timing ($p \leq 0.10$) occurred at 23 of 47 site-years with higher IE_E at 7 and 16 of 23 site-years for N applied at-planting and split-applied N, respectively.

2.3.2.2 Grain Dry Matter at the Economic Optimum Nitrogen Rate

Grain dry matter had a positive quadratic-plateau response to N rate (0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) at 91 of 98 site-years and N application timings ($p \leq 0.10$, Table 11). At one site-year and application timing (2015 WI N applied at-planting), GDM response to N rate was best fit to a quadratic equation ($p \leq 0.10$). At the remaining six site-years and application timings GDM did not respond to N rate ($p > 0.10$).

Estimated GDM values at the EONR (GDM_E) ranged from 5,191 to 14,449 kg ha^{-1} with an average of 11,064 kg ha^{-1} (Table 11). The GDM_E did not differ between N application timing ($p > 0.10$) at 29 of 49 site-years. Where timing affected GDM_E, half were greater with at-planting and half were greater with split N application. Across all site-years and N application timing, GDM_E was not related to IE_E or EONR ($p > 0.10$; data not shown).

2.3.2.3 Plant Nitrogen Content at Physiological Maturity at the Economic Optimum Nitrogen Rate

Plant N content at physiological maturity (PMN) responded positively to N rate (0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) ($p \leq 0.10$) quadratically or linearly at 74 and 17 of 94 site-years and N application timings, respectively (Table 12, 2015 ND data missing). At three site-years and N application timings, PMN was non-responsive to N rate ($p > 0.10$).

The estimated PMN at the EONR (PMN_E) ranged from 107 to 359 kg ha^{-1} among the site-years with an average of 212 kg ha^{-1} (Table 12). Within a site-year, PMN_E did not differ between N application timing at 24 of 47 site-years ($p > 0.10$). When N application timing affected PMN_E (23 of 47 site-years, $p \leq 0.10$), PMN_E was higher more often when N was applied at-planting (16 site-year) than when split-applied (7 site-years). The IE_E decreased with increased PMN_E ($p \leq 0.10$, r = -0.65, n = 94, Fig. 18) across all site-years and N application timings.

2.3.2.4 Grain Nitrogen Concentration at the Economic Optimum Nitrogen Rate

The grain N concentration (GNC) increased with higher N rate (0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) ($p \leq 0.10$) linearly or quadratically at 41 and 49, respectively, of 94 site-years and N application timings (Table 13, 2015 ND data missing). Grain N concentration responded negatively to N rate at one site-year and N application timing ($p \leq 0.10$). There was no response in GNC to N rate at three site-years and N application timings ($p > 0.10$).

Estimated values of GNC at the EONR (GNC_E) ranged from 9.2 to 14.4 g kg^{-1} with an average of 11.8 g kg^{-1} (Table 13). Within a site-year, 26 of 47 site-years GNC_E did not differ between application timing ($p > 0.10$). Grain N concentration differed between N application timings at 21 of 47 site-years ($p \leq 0.10$) and higher GNC_E was split about equally for N applied at-planting (10 site-years, average 12.4 g kg^{-1}) or split-applied N (11 site-years, average 12.0 g kg^{-1}). Grain N concentration at the EONR had a negative linear relationship with IE_E ($p \leq 0.10$, r = -0.68, n = 94, Fig. 19) across all site-years and N application timings.

2.3.2.5 Stover Nitrogen Concentration at the Economic Optimum Nitrogen Rate

At each site-year and N application timing, stover N concentration (SNC) increased with increased N rate linearly or quadratically, at 72 or 19 of 98 site-years and N application timings, respectively, ($p \leq 0.10$, Table 14). Stover N concentration decreased with increasing N rate at three site-years and N application timings ($p \leq 0.10$). There were four site-years and N application timings where SNC was non-responsive to N rate ($p > 0.10$).

Estimated values of SNC at the EONR (SNC_E) ranged from 5.0 to 14.6 g kg^{-1} with an average of 8.6 g kg^{-1} across all site-years and N application timings (Table 14). Within a site-year, SNC_E did not respond to N application timings at 29 of 49 site-years ($p > 0.10$). At the other 20 site-years, applying N at planting produced higher SNC_E at 9 site-years (average 9.1 g kg^{-1}), and split N produced higher SNC_E at 11 site-years (average 9.2 g kg^{-1}). Across all site-years and N application timings, SNC_E was negatively correlated to IE_E ($p \leq 0.10$, r = -0.59, n = 94, Fig. 20).

2.3.2.6 Stover Dry Matter at the Economic Optimum Nitrogen Rate

Across all site-years and N application timings, stover dry matter (SDM) increased linearly, quadratically, or in a quadratic-plateau relationship with higher N rates at 19, 38, or 26 of 98 site-years, respectively, and N application timings ($p \leq 0.10$, Table 15). There was one site-year and N application timing where SDM decrease linearly with higher N rates ($p \leq 0.10$). At 14 site-years and N application timing SDM was non-responsive to N rate ($p > 0.10$).

Estimated values of SDM at the EONR (SDM_E) ranged from 3,947 to 12,663 kg ha^{-1} with an average of 7,991 kg ha^{-1} across all site-years and N application timings (Table 15). Within a site-year, SDM_E did not differ between N application timing at 25 of 49 site-years ($p > 0.10$). Differences in SDM_E between N applications timing occurred at 24 of 49 site-years ($p \leq 0.10$) with higher SDM_E produced at 22 and 2 site-years for N applied at-planting or spilt-applied, respectively. Across all site-years and N application timings, SDM_E had a negative relationship with IE_E ($p \leq 0.10$, r = -0.61, n = 94, Fig. 21).

2.3.3 Weather Variables as Predictors of Internal N Efficiency at the Economic Optimum N Rate

2.3.3.1 Total Rainfall and Abundant and Well-Distributed Rainfall

In general, rainfall amounts during different periods of the growing season was not correlated with IE_E across all site-years ($p > 0.10$, Table 16). The abundant and well-distributed rainfall (AWDR) during different periods of the growing season had inconsistent relationship with IE_E (Table 16). However, AWDR two weeks after tasseling ($AWDR_{2wkAVT}$) was negatively correlated with IE_E ($p \leq 0.10$, r = -0.28, n = 94; Table 16) and ranged from 0 to 103 with an average of 15 across all site-years (Table 8). The distribution of rainfall during the two week period before and after tasseling ($AWDR_{2wkBAVT}$) ranged from 0 to 164 with an average of 50 and was not correlated with IE_E ($p > 0.10$), because $AWDR_{2wkBAVT}$ was positively correlated to IE_E in 2014 ($p \leq 0.10$, r = 0.39) and negatively correlated in 2016 (r = -0.40); Table 16).

2.3.3.2 Temperature

Across all site-years, high or low temperature during portions of the growing season were not correlated with IE_E ($p > 0.10$, Table 17), even though, some of these variables were moderately correlated with IE_E for one or two years of the three years ($p \leq 0.10$). For example, in 2014 and 2016 the mean high temperature approximately two weeks after tasseling (HT_{2wkAVT}) was negatively correlated with IE_E ($p \leq 0.10$, r = -0.44 and -0.55, respectively, Table 17), and varied from 26 to 35°C with an average of 29°C (Table 18). In 2015, HT_{2wkAVT} was positively correlated with IE_E ($p \leq 0.10$, r = 0.39) and ranged from 28 to 31°C with an average of 29°C. Mean high temperature during grain fill (HT_{GF}) was correlated with IE_E for each individual year ($p \leq 0.10$). However, HT_{GF} was negatively correlated with IE_E in 2014 and 2016 ($p \leq 0.10$, r = -0.41 and -0.52, respectively) and varied from 25 to 32°C with an average of 33°C. In contrast, HT_{GF} in 2015 was positively correlated with IE_E ($p \leq 0.10$, r = 0.41) and ranged from 26 to 32°C with an average of 28°C. Thus, HT_{GF} was not correlated with IE_E across all site-years (p> 0.10).

2.3.4 Soil Variables as Predictors of Internal N Efficiency at the Economic Optimum N Rate

2.3.4.1 Soil Texture

In general, clay, silt, and sand concentrations were strongly correlated with each other ($p \leq 0.10$). Silt and sand concentrations were correlated with IE_E across all site-years ($p \leq 0.10$, r = -0.22 and +0.24, respectively, Table 19), but clay content was not correlated with IE_E ($p > 0.10$). Silt content varied from 23 to 910 g kg^{-1} with an average of 469 g kg^{-1} and sand content varied from 23 to 910 g kg^{-1} with an average of 267 g kg^{-1} (Table 20). These relationships were influenced primarily by the correlation in 2015 ($p \leq$ 0.10, silt: r = -0.33 and sand: r = 0.33) and 2016 (silt: r = -0.37 and sand: r = 0.40). There was no correlation between silt or sand content with IE_E in 2014 ($p > 0.10$).

2.3.4.2 Organic Matter Concentration

Organic matter concentration in the Ap horizon determined by total organic carbon (OM_2), thermo-gravimetric analyzer (OM_3), or by loss on ignition in the upper 0-15 cm of soil (ROM), were highly correlated ($p \leq 0.10$, $0.74 \leq r \leq 0.93$). Across all years, OM_2, OM_3, and ROM ranged from 12 to 64, 11 to 56, and 11 to 69 g kg^{-1}, respectively (Table 20). There was no correlation between IE_E and any measure of OM across all years ($p > 0.10$, Table 19), despite positive correlations between IE_E and OM in 2014 ($p \leq$ 0.10, $0.40 \leq r \leq 0.44$). Routine organic matter and OM_3 were negatively correlated with IE_E in 2015 ($p \leq 0.10$, r = -0.69 and -0.33, respectively). There was no correlation between OM_2 with IE_E in 2015 ($p > 0.10$). In 2016, no measurement of OM (OM_2, OM_3, and ROM) was correlated with IE_E ($p > 0.10$).

2.3.4.3 Soil Nitrate-Nitrogen

Soil NO_3-N measured pre-plant (PPNT), pre-sidedress (PSNT), and tasseling (VTNT) (at all depths) were correlated with each other across all three years ($p \leq 0.10$, $0.29 \leq r \leq 0.84$), but post-harvest (PHNT) was not correlated with PPNT or PSNT ($p >$ 0.10) and was only weakly correlated with VTNT at the 30-60 cm depth ($VTNT_0$30-60) ($p \leq 0.10$, $0.20 \leq r \leq 0.41$). Across all site-years, PPNT varied from 1.0 to 16.8, 0.5 to 10.7, and 0.5 to 10.0 mg kg^{-1} for soil NO_3-N at the 0-30 (PPNT0-30), 30-60 (PPNT30-

60), and 60-90 (PPNT60-90) cm depths, respectively (Table 21). There was a weak correlation between PPNT0-30, PPNT30-60, and PPNT0-60 (averaged over the 0-30 and 30-60 cm depth) with IE_E across all three years ($p \leq 0.10$, r = -0.19, -0.20, and -0.21, respectively, Table 22), however, in all individual years PPNT0-30 and PPNT30-60 was not correlated with IE_E ($p > 0.10$). The PPNT0-60 was only correlated with IE_E in 2014 ($p \leq 0.10$, r = -0.31).

Across all three years, soil NO_3-N with no N fertilizer at PSNT ($PSNT_0$) varied from 2.4 to 22.9, 3.0 to 22.3, and 2.8 to 19.4 mg kg^{-1} at the 0-30 ($PSNT_0$0-30), 30-60 ($PSNT_0$30-60), and 0-60 cm depths ($PSNT_0$0-60) (averaged over 0-30 and 30-60 cm depths), respectively (Table 21). With 45 kg N ha^{-1} applied at planting, extractable soil N ($PSNT_{45}$) across all three years varied from 4.3 to 31.3, 3.3 to 17.1, and 3.8 to 22.2 mg kg^{-1} at the 0-30 ($PSNT_{45}$0-30), 30-60 ($PSNT_{45}$30-60), and 0-60 cm depths ($PSNT_{45}$0-60) (averaged over 0-30 and 30-60 cm depths), respectively (Table 21). Pre-sidedress soil NO_3-N of the non-fertilizer and 45 kg N ha^{-1} treatments at all depths were not related to IE_E for any individual year or across all three years ($p > 0.10$, Table 22).

Across all three years, VTNT for the non-fertilized treatment ($VTNT_0$) varied from 0.5 to 16.3, 0.5 to 12.2, and 0.6 to 11.6 mg kg^{-1} at the 0-30 ($VTNT_0$0-30), 30-60 ($VTNT_0$30-60), and 0-60 cm depth ($VTNT_0$0-60) (averaged over 0-30 and 30-60 cm depth), respectively (Table 23). Across all site-years, VTNT (at all depths) was not correlated with IE_E ($p > 0.10$, Table 22). For individual years, VTNT (at any soil depth) was only correlated with IE_E in 2014 ($p \leq 0.10$, $r \leq 0.44$) and in 2015 at 0-30 cm depth.

Across all three years, PHNT of the non-fertilizer treatment ($PHNT_0$) varied from 0.9 to 8.1, 0.5 to 2.5, and 0.5 to 2.5 mg kg^{-1} at the 0-30 ($PHNT_0$0-30), 30-60 ($PHNT_0$30-60), and 60-90 cm depth ($PHNT_0$60-90), respectively (Table 23). Similar variability was observed at the 45 kg N ha^{-1} treatment at the 0-30 ($PHNT_{45}$0-30: 0.8 to 9.0 mg kg^{-1}), 30-60 ($PHNT_{45}$30-60: 0.5 to 4.5 mg kg^{-1}), and 60-90 cm depths ($PHNT_{45}$60-90: 0.5 to 2.5 mg kg^{-1}). Both $PHNT_0$ and $PHNT_{45}$ (at all depths) were negatively correlated with IE_E ($p \leq 0.10$, $-0.22 \geq r \leq -0.30$, Table 22), except for $PHNT_0$60-90 ($p > 0.10$). Soil NO_3-N at the 0-60 depths ($PHNT_0$0-60: averaged over 0-30 and 30-60 cm depth) and 0-90 cm depth ($PHNT_0$0-90: averaged over the 0-30, 30-60 and 60-90 cm depths) for non-fertilizer and 45 kg N ha^{-1} ($PHNT_{45}$0-60 and $PHNT_{45}$0-90) treatments were negatively correlated with

IE_E across all three years ($p \leq 0.10$, $-0.28 \geq r \leq -0.33$). Post-harvest soil NO_3-N at the non-fertilizer and 45 kg N ha^{-1} treatments were correlated with IE_E at the 0-30, 30-60, 60-90, 0-60, and 0-90 across all three years and were primarily influenced by the correlations in 2016 ($p \leq 0.10$, $-0.30 \leq r \leq -0.65$).

2.3.4.3.1 Soil Nitrate, Weather, and Soil Texture Interaction

Across all three years, the combination of soil NO_3-N (PPNT0-60, $PHNT_0$0-60, or $PHNT_{45}$0-60) with soil texture (silt content) and temperature ($HT_{2wkBAVT}$) (PPNT0-60, $PHNT_0$0-60, or $PHNT_{45}$0-60*Silt Content*$HT_{2wkBAVT}$) were negatively correlated with IE_E ($p \leq 0.10$, r = -0.26, -0.34, and -0.37, respectively, Table 22). In 2015, PPNT0-60*Silt Content*$HT_{2wkBAVT}$ and $PHNT_{45}$0-60*Silt Content*$HT_{2wkBAVT}$ were negatively correlated with IE_E ($p \leq 0.10$, r = -0.34 and -0.37, respectively, Table 22), but $PHNT_0$0-60*Silt Content*$HT_{2wkBAVT}$ was not correlated with IE_E in 2015 ($p > 0.10$). In 2016, all three combinations (PPNT0-60, $PHNT_0$0-60, or $PHNT_{45}$0-60*Silt Content*$HT_{2wkBAVT}$) were negatively correlated with IE_E ($p \leq 0.10$, r = -0.31, -0.68, and -0.66, respectively). The correlation between $PHNT_0$0-60 or $PHNT_{45}$0-60*Silt Content*$HT_{2wkBAVT}$ with IE_E were mainly due to the correlation in 2016 ($PHNT_0$0-60*Silt Content*$HT_{2wkBAVT}$, r = -0.68 and -0.66, respectively). There was no correlation in 2014 for any of the three combinations with IE_E ($p > 0.10$).

2.3.4.4 Plant Available Water Content

The estimated plant available water content (PAWC) retrieved from the Soil Survey Geographic database (SSURGO) at the 0-30 (PAWC0-30), 30-60 (PAWC30-60), and 60-90 (PAWC60-90) cm soil depth along with the average PAWC (averaged over all depths, PAWC0-90) were all highly correlated with one another across all three years ($p \leq 0.10$, $0.34 \geq r \leq 0.75$). Values for PAWC (PAWC0-30, PAWC30-60, PAWC60-90, and PAWC0-90) varied from 0.01 to 0.23 cm cm^{-1} (Table 20). In general, PAWC (at each depth and averaged over each depth) were negatively correlated with IE_E across all three years ($p \leq 0.10$, $-0.25 \geq r \leq -0.36$, Table 19). These relationships were primarily influenced by the negative relationships between PAWC and IE_E in 2015 at most depths and averaged over each depth ($p \leq 0.10$, $-0.34 \geq r \leq -0.40$) and in 2016 ($-0.29 \geq r \leq -0.40$).

There was no relationship between PAWC (at any depth or averaged over each depth) with IE_E in 2014 ($p > 0.10$).

Across all three years, PAWC (at each depth and averaged over each depth) were positively correlated with silt content ($p \leq 0.10$, $0.34 \leq r \geq 0.55$, Table 24) and negatively correlated with sand content ($-0.23 \leq r \geq -0.42$). Plant available water content (at each depth and averaged over each depth) were positively correlated with SDM_E ($p \leq 0.10$, $0.30 \geq r \leq 0.37$) and SDM of the 0 and 45 kg N ha^{-1} rate ($0.20 \geq r \leq 0.36$ and $0.29 \geq r \leq 0.41$, respectively, Table 24). Soil NO_3-N at different times during the growing season (PPNT, PSNT, and PHNT at each depth and N treatments (0 and 45 kg N ha^{-1})) were generally not correlated with PAWC (PAWC0-30, PAWC30-60, PAWC60-90, and PAWC0-90), except for $VTNT_0$0-30 and $VTNT_0$0-60 which were negatively correlated with PAWC (PAWC30-60, PAWC60-90, and PAWC0-90). The combinations of variables between PPNT0-60*Silt content*$HT_{2wkBAVT}$ was positively correlated with PAWC (at all depths) across all three years ($p \leq 0.10$, $0.27 \geq r \leq 0.42$).

2.3.5 Crop Reflectance Variables

Red reflectance at the non-fertilizer (R_0) and 45 kg N ha^{-1} (R_{45}) treatments varied from 3.7 to 14.2 (Table 25). There was no correlation between IE_E and R_0 or R_{45} across all three years ($p > 0.10$, Table 26). The near infrared reflectance of the non-fertilizer (NIR_0) and 45 kg N ha^{-1} (NIR_{45}) treatments varied from 30 to 47 (Table 25) and was not correlated with IE_E across all site-years ($p > 0.10$, Table 26). This was surprising for NIR_{45} since there were moderate correlations in 2014 ($p \leq 0.10$, $r = -0.40$) and 2015 ($r = -0.40$).

The normalized difference vegetation index of the non-fertilizer ($NDVI_0$) and 45 kg N ha^{-1} ($NDVI_{45}$) treatments varied from 0.36 to 0.85 across all three years (Table 25) and was not correlated with IE_E ($p > 0.10$, Table 26).

The red edge reflectance of the non-fertilizer (RE_0) or 45 kg N ha^{-1} (RE_{45}) treatments varied from 18 to 22 across all three years (Table 27). The RE_0 was positively correlated with IE_E across all three years ($p \leq 0.10$, $r = 0.20$, Table 26) due to positive correlations in 2014 ($p \leq 0.10$, $r = 0.60$) and 2015 ($p \leq 0.10$, $r = 0.48$). The RE_{45} was not correlated with IE_E across all three years ($p > 0.10$), even though there were positive correlations with IE_E in 2014 ($p \leq 0.10$, r = 0.54) and 2015 ($p \leq 0.10$, r = 0.37).

The normalized difference red edge of the non-fertilizer ($NDRE_0$) or 45 kg N ha^{-1} ($NDRE_{45}$) treatments varied from 0.17 to 0.44 (Table 27) and were negatively correlated with IE_E in 2014 ($p \leq 0.10$, r = -0.60 and -0.55, Table 26), 2015 (r = -0.48 and -0.38), and across all three years (r = -0.21 and -0.18, respectively).

Sufficiency indices for NDVI or NDRE, calculated by dividing reflectance of the non-fertilizer or 45 kg N ha^{-1} treatments by reflectance of the 225 or 270 kg N ha^{-1} treatments (NDVI indices [$NDVI_0225$, $NDVI_0270$, $NDVI_{45}225$, and $NDVI_{45}270$] or NDRE indices [$NDRE_0225$, $NDRE_0270$, $NDRE_{45}225$, and $NDRE_{45}270$]) varied from 0.51 to 1.17 across all three years (Table 28 and 29). The simple ratio sufficiency indices for NDVI or NDRE ((SI_{R0} or SI_{R45}) and (SI_{R0} or SI_{RE45}), calculated by R_0 or RE_0 and NIR_0 or R_0 or RE_{45} and NIR_{45} divided by the average R or RE and NIR value of the 225 and 270 kg N ha^{-1} as the N rich treatment) varied from 0.85 to 1.76 (Table 28 and 29). There were negative correlations between IE_E and each sufficiency indices and simple ratio indices (NDVI and NDRE) across all three years ($p \leq 0.10$, Table 26), however none exceeded an r-value of -0.32. These correlations were influenced primarily by correlations in 2014 ($p \leq 0.10$, $-0.34 \leq r < -0.54$, Table 26) and 2015 ($-0.33 \leq r < -0.51$).

Across all three years, sufficiency indices and simple ratios for NDVI ($NDVI_0225$, $NDVI_0270$, $NDVI_{45}225$, $NDVI_{45}270$, SI_{R0}, and SI_{R45}) and NDRE ($NDRE_0225$, $NDRE_0270$, $NDRE_{45}225$, $NDRE_{45}270$, SI_{RE0}, and SI_{RE45}) were correlated with GNC_E (NDVI indices [$r \leq 0.51$, Table 30] and NDRE indices [$r \leq 0.55$, Table 31]). These sufficiency indices and simple ratios (NDVI and NDRE) were also correlated with PPNT0-30 and PSNT of the 0 and 45 kg N ha^{-1} treatments at the 0-30 cm depth (NDVI indices [$r \leq 0.54$, $r \leq 0.64$, and $r \leq 0.61$, respectively, Table 30] and NDRE indices [$r \leq 0.61$, $r \leq 0.76$, and $r \leq 0.74$, respectively, Table 31]).

2.3.6 Plant Variables

2.3.6.1 Plant N Content at Tasseling

Across all three years, VT plant N content with zero N applied (VTN_0) and 45 kg N ha^{-1} (VTN_{45}) treatments varied from 32 to 160 kg N ha^{-1} and 36 to 210 kg N ha^{-1}, respectively. Plant N content at VT (VTN_0 and VTN_{45}) was negatively correlated with IE_E ($p \leq 0.10$, r = -0.42 and -0.50, respectively, n = 90 site-years, Table 32, Fig. 22A and B). The VTN_0 and VTN_{45} had moderate to strong relationships in 2014 ($p \leq 0.10$, $VTN_{0:}$ r = -0.72 and VTN: r = -0.74) and 2015 (VTN_0: r = -0.53 and VTN_{45}: r = -0.52), but there was no relationship between VTN_0 and IE_E in 2016 ($p > 0.10$). However, VTN_{45} was negatively correlated to IE_E in 2016 ($p \leq 0.10$, r = -0.56).

Across all three years, VTN_0 and VTN_{45} were positively correlated with PMN_E ($p \leq 0.10$, r = 0.42 and 0.54) and SNC_E (r = 0.45 and 0.51, respectively, Table 33). The PAWC0-30 was positively related to VTN_0 and VTN_{45} across all three years ($p \leq 0.10$, r = 0.33 and 0.36, respectively), but PAWC at the 30-60, 60-90, and averaged over all depths (0-90 cm depth) were not correlated with VTN_0 or VTN_{45} ($p > 0.10$). The combination of soil NO_3-N at PPNT0-60 with silt content and high temperature two-weeks before and after VT was positively correlated with VTN_0 and VTN_{45} ($p \leq 0.10$, r = 0.59 and 0.49, respectively). Sufficiency indices and simple ratios for NDVI ($NDVI_0225$, $NDVI_0270$, $NDVI_{45}225$, $NDVI_{45}270$, SI_{R0}, and SI_{R45}) and NDRE ($NDRE_0225$, $NDRE_0270$, $NDRE_{45}225$, $NDRE_{45}270$, SI_{RE0}, and SI_{RE45}) were correlated with VTN_0 and VTN_{45} (NDVI indices [r ≤ 0.54 and r ≤ 0.59, Table 33] and NDRE indices [r ≤ 0.53 and r ≤ 0.54, respectively, Table 33]) across all three years.

2.3.6.1.1 Predictive Models for Internal Nitrogen Efficiency at the Economic Optimum Nitrogen Rate

Using only variables that could be acquired prior to planting, the best multivariate linear model to predict IE_E consisted of PAWC0-30 (-82.5 ± 19.6 cm cm^{-1}) and PPNT0-60 (-0.2958 ± 0.1302 mg kg^{-1}) ($p \leq 0.10$, Intercept = 72.7 ± 4.2, adjusted R^2 = 0.19, n = 88, Table 34). If variables collected prior to V9 (±1V growth stage) were utilized to predict IE_E, considerably more variation in IE_E could be explained (Table 34, adjusted R^2 = 0.47, n = 84 site-years). Variables in order of inclusion in the model were PAWC0-30 $NDVI_{45}225$, OM_3, CEC, $PSNT_{45}0$-30, PPNT0-60, $NDRE_0$, and pH salt (pH_s). Six variables (PAWC0-30, $NDVI_{45}225$, OM_3, CEC, $PSNT_{45}0$-30, and PPNT0-60) resulted in a negative response in IE_E and two variables (OM_3 and $PSNT_{45}0$-30) resulted in positive response in IE_E.

A model was developed to predict IE_E from variables taken no later than ten days after post-sidedress (V9 ± 1 V stage) (Table 34). This model consisted of ten variables collected prior to sidedress (V9±1 V-stage) ($p \leq 0.10$, adjusted $R^2 = 0.62$, n = 84 site-years). Six of the variables were listed in the previous model (PAWC0-30, $NDVI_{45}$225, OM_3, CEC, $PSNT_{45}$0-30, and PPNT0-60) while four additional variables were added to the model ($AWDR_{10dASN}$, $NDRE_{45}$, pH-water (pH_w), and $AWDR_{10dBSN}$). Three of the four variables ($NDRE_{45}$, pH_w, and $AWDR_{10dBSN}$) added into this model resulted in a negative response in IE_E and one ($AWDR_{10dASN}$) resulted in a positive response in IE_E. These ten variables were included into the model in the order of PAWC0-30, $NDVI_{45}$225, $AWDR_{10dASN}$, OM_3, CEC, $PSNT_{45}$0-30, PPNT0-60, $NDRE_{45}$, pH_w, and $AWDR_{10dBSN}$.

Five variables available at or before VT were related to IE_E ($p \leq 0.10$, n = 70 site-years, adjusted $R^2 = 0.54$, Table 34). The variable explaining the most variation in IE_E was VTN_{45}, which was negatively related to IE_E ($R^2 = 0.34$). Plant available water content at the 60-90 cm explained 11% of the variation in IE_E. The remaining three variables (OM_2, clay, and $AWDR_{10dASN}$) included in the model had partial $R^2 \leq 0.05$.

2.3.6.2 Plant N Content at Physiological Maturity

Across all three years, plant N content at R6 of the non-fertilized (PMN_0) and 45 kg N ha^{-1} (PMN_{45}) treatments were negatively correlated with IE_E ($p \leq 0.10$, r = -0.28 and -0.38, respectively, n = 94 site-years, Table 32). The PMN_0 and PMN_{45} varied from 36 to 243 kg ha^{-1} and 44 to 265 kg ha^{-1}, respectively, across all three years (Table 35). In 2014 and 2015, PMN_0 and PMN_{45} were negatively correlated to IE_E ($p \leq 0.10$, 2014 [r = -0.38 and -0.44] and 2015 [r = -0.41 and -0.36, respectively]). The PMN_{45} was also negatively correlated with IE_E in 2016 ($p \leq 0.10$, r = -0.44), but PMN_0 was not correlated to IE_E in 2016 ($p > 0.10$).

Across all three years, PMN_E and SNC_E were positively correlated with PMN_0 ($p \leq 0.10$, r = 0.40, 0.43 and 0.43, Table 33) and PMN_{45} (r = 0.52, 0.57 and 0.51, respectively). Plant available water content at the 0-30 cm depth was positive correlated with PMN_0 and PMN_{45} across all three years ($p \leq 0.10$, r = 0.22 and 0.28, respectively), but was not correlated with PAWC at greater depths ($p > 0.10$). The soil NO_3-N at PPNT0-60*silt content*$HT_{2wkBAVT}$ was positively correlated with PMN_0 ($p \leq 0.10$, r =

0.55) and PMN_{45} (r = 0.46). Sufficiency indices and simple ratios for NDVI ($NDVI_0225$, $NDVI_0270$, $NDVI_{45}225$, $NDVI_{45}270$, SI_{R0}, and SI_{R45}) and NDRE ($NDRE_0225$, $NDRE_0270$, $NDRE_{45}225$, $NDRE_{45}270$, SI_{RE0}, and SI_{RE45}) were correlated with PMN_0 and PMN_{45} (NDVI indices [$p \leq 0.10$, r ≤ 0.49 and r ≤ 0.52, Table 33] and NDRE indices [$p \leq 0.10$, r ≤ 0.57 and r ≤ 0.52, respectively, Table 33]).

2.3.6.3 Harvest Index

Harvest index at the non-fertilized (HI_0) and 45 kg N ha^{-1} (HI_{45}) treatments were positively correlated to IE_E across all three years ($p \leq 0.10$, n = 94, r = 0.39 and 0.44, respectively, Table 32, Fig. 23A and B). Over all three years, HI_0 and HI_{45} varied from 0.30 to 0.67 and 0.31 to 0.68, respectively. In 2014 and 2016, HI_0 and HI_{45} were positively correlated to IE_E ($p \leq 0.10$, 2014 [r = 0.48 and 0.56] and 2016 [r = 0.61 and 0.65, respectively]), but neither were correlated in 2015 ($p > 0.10$).

Across all three years, SDM_E was negatively correlated with HI_0 ($p \leq 0.10$, r = -0.61, Table 33) and HI_{45} (r = -0.59), but was not correlated with GDM_E, GNC_E, PMN_E, and SDM_E ($p > 0.10$). There was a positive correlation between PMN_0 with HI_0 ($p \leq 0.10$, r = 0.46) and HI_{45} (r = 0.43). The PAWC0-30 was negatively related with HI_0 ($p \leq 0.10$, r = -0.24) and HI_{45} (r = -0.24) across all site-years. Harvest index at non-fertilized and 45 kg N ha^{-1} treatments were positively correlated with the amount of soil NO_3-N at PPNT0-30, $PSNT_0$0-30, and $VTNT_0$0-30 ($p \leq 0.10$, PMN_0 [r = 0.26, 0.40, and 0.33, respectively] and PMN_{45} [r = 0.27, 0.38, and 0.36, respectively]).

2.3.6.4 Nitrogen Harvest Index

Across all three years N harvest index at non-fertilized (NHI_0) and 45 kg N ha^{-1} (NHI_{45}) treatments varied from 0.44 to 0.72 and 0.40 to 0.72, respectively, and were positively correlated to IE_E across all three years ($p \leq 0.10$, r = 0.39 and 0.47, respectively, Table 32, Fig. 24A and B). In 2014 and 2016, NHI_0 and NHI_{45} were positively correlated to IE_E ($p \leq 0.10$, 2014 [r = 0.56 and 0.67] and 2016 [r = 0.42 and 0.58, respectively]). In 2015, NHI_0 and NHI_{45} were not correlated with IE_E ($p > 0.10$).

Nitrogen harvest index at non-fertilized and 45 kg N ha^{-1} treatments were negatively correlated with PMN_E, SDM_E, and SNC_E ($p \leq 0.10$, PMN_E [r = -0.32 and -

0.34, Table 33], SDM_E [r = -0.62 and -0.61], and SNC_E [r = -0.35 and -0.45, respectively] Table 33), but no correlation between GDM_E and GNC_E ($p > 0.10$). Plant available water content at the 0-30 cm depth was negatively correlated with NHI_0 and NHI_{45} across all three years ($p \leq 0.10$, r = -0.39 and -0.37, respectively). The NHI_0 and NHI_{45} were positively correlated to the amount of soil NO_3-N at PPNT0-30, $PSNT_0$0-30, and $VTNT_0$0-30 ($p \leq 0.10$, PPNT0-30 [r = 0.25 and 0.25], $PSNT_0$0-30 [r = 0.44 and 0.44], and $VTNT_0$0-30 [r = 0.53 and 0.50, respectively]) across all three years.

2.3.6.5 Net Change in Stover Nitrogen Content between Tasseling and Physiological Maturity

Across all site-years the net change in stover N content between tasseling and physiological maturity of the non-fertilized (ΔNCS_0) and 45 kg N ha^{-1} (ΔNCS_{45}) treatments varied from -1 to -113 and -1 to -143 kg N ha^{-1}, respectively, (Table 35) and were negatively correlated to IE_E ($p \leq 0.10$, Table 32), but the correlation was weak ($p \leq 0.10$, NHI_0 [r = 0.23] and NHI_{45} [r = 0.23], n = 90 site-years). Increase in ΔNCS_0 and ΔNCS_{45} were negatively correlated to IE_E in 2014 ($p \leq 0.10$, r = 0.58 and 0.57) and 2015 (r = 0.39 and 0.36, respectively), but there was not a correlation in 2016 ($p > 0.10$).

The ΔNCS_0 and ΔNCS_{45} were negatively correlated with two of five components of IE_E ($p \leq 0.10$, GNC_E [r = -0.28 and -0.27] and SNC_E [r = -0.26 and -0.20, respectively], Table 33), but not correlated with GDM_E, PMN_E, and SDM_E ($p > 0.10$). There was a negative relationship between ΔNCS_0 and ΔNCS_{45} with PAWC0-30 ($p \leq 0.10$, r =-0.25 and -0.23, respectively) across all site-years. The soil NO_3-N at PPNT0-30, $PSNT_0$0-30, and $VTNT_0$0-30 were correlated with ΔNCS_0 ($p \leq 0.10$, r = -0.39, 0.44, and 0.53) and ΔNCS_{45} (r = -0.19, 0.44, and 0.50, respectively). The combined factors of PPNT0-60*Silt Content*$HT_{2wkBAVT}$ was negatively correlated with ΔNCS_0 ($p \leq 0.10$, r = -0.58) and ΔNCS_{45} (r = -0.43).

2.3.7 Hybrid

Across all hybrids, IE_E, varied from 38 to 73 kg GDM kg^{-1} N, averaging 54 kg GDM kg^{-1} N. Of the nine hybrids included in the study, P1498, P0987, and P1197 were examined in multiple environments: 8, 9, and 11 site-years, respectively. Internal N efficiency at the EONR for hybrid P1498 varied from 41 to 65 kg GDM kg^{-1} N (Fig. 25) with an average of 53 kg GDM kg^{-1} N and a standard deviation of 7 kg GDM kg^{-1} N (Fig. 26) For hybrid P0987, IE_E varied from 45 to 61 kg GDM kg^{-1} N (Fig. 25) with an average of 53 kg GDM kg^{-1} N and a standard deviation of 4 kg GDM kg^{-1} N (Fig. 26) across site-years and N application timings. Internal N efficiency at the EONR for hybrid P1197 varied from 38 to 69 kg GDM kg^{-1} N (Fig. 25) and averaged 53 kg GDM kg^{-1} N and a standard deviation of 9 kg GDM kg^{-1} N (Fig. 26) across sites and N rate timings.

2.4 Discussion

2.4.1 Nitrogen Response in Indiana

Grain dry matter, PMN, and IE in 2014 and 2016 is discussed separate from 2015 result because of an outbreak of NCLB which correlated with GDM, PMN, and IE.

2.4.1.1 Grain Dry Matter

In 2014, averaged across Indiana sites and N application timings, GDM increased quadratically with increasing N rates (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments). However, other studies noted GDM response to N was quadratic, but plateaued at higher N rates (0 to 225 in 45 kg N ha^{-1} increments or 0 to 224 kg N ha^{-1} in 56 kg N ha^{-1} increments) (Pantoja et al., 2015; Woli et al., 2016, respectively). Although, in this study the 0 and 45 kg N ha^{-1} treatments were excluded from the analysis, thus, possibly masking GDM quadratic-plateau response to higher N rates.

In 2014 averaged across N rates and productivity sites in IN, N split-applied had higher GDM (11,574 kg ha^{-1}) than N applied at-planting (11,163 kg ha^{-1}). This could be a possible result from better distribution of rainfall during the vegetative period (231), especially ten days before and after split-applied N $AWDR_{10dBSN}$ = 105), compared to 2015 (143 and 2) and 2016 (78 and 4, respectively), which may have led to greater potential for N loss and plant stress from low availability of N with N applied at-planting compared to N split-applied. Soil NO_3-N at tasseling was lower with N applied at-planting compared to N split-applied and VTN (averaged over productivity site and N rate 90 to 315 kg N ha^{-1}) was similar between timings, which perhaps indicates more N available heading into grain fill period and increased GDM compared to N applied at-planting. In a meta-analysis of 51 N response studies noted, more frequent rain events 15 days before and 30 days after sidedress (> 99) at 23 of the 51 studies increased N loss through leaching and/or denitrification compared to less frequent rain events (< 99) at 28 of the 51 studies (Tremblay et al., 2012).

In 2016 in the low productivity site in IN, GDM weak linear response to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) was perhaps attributed to PMN weak response to N rate especially with N split-applied (AP = 0.289 kg N ha^{-1} vs S = 0.072 kg N ha^{-1}), which increased 66 kg N ha^{-1} or 24 kg N ha^{-1} from the lowest to highest value for N applied at-planting and split, respectively. In contrast, GDM in the high productivity site response to N rate was quadratic possibly attributed to a larger response in PMN (AP = 0.339 kg N ha^{-1} vs S = 0.319 kg N ha^{-1}), which increased 76 kg N ha^{-1} or 79 kg N ha^{-1} from the lowest to highest value of PMN for N applied at-planting and split, respectively.

2.4.1.2 Plant Nitrogen Content at Physiological Maturity

In 2014 at the low and high productivity site in IN, the increase in PMN in response to increased N rates (averaged across N application timing) was quadratic. Several other N response studies found PMN responded quadratically to N rates ranging from, 0 to 210 kg N ha^{-1} in 30 kg N ha^{-1} increments, and 0 to 225 kg N ha^{-1} in 45 kg N ha^{-1} increments 0 to 224 kg N ha^{-1} in 56 kg N ha^{-1} increments (Abbasi et al., 2012; Pantoja et al., 2015; Woli et al., 2016, respectively). In the low productivity site, N split-applied resulted in higher PMN than N applied at-planting. The distribution of rainfall was better in 2014 during the vegetative period ($AWDR_{Vege}$ = 239), especially ten days before N was split-applied ($AWDR_{10dBSN}$ = 105), compared to 2015 (143 and 2) and 2016 (78 and 4, respectively). Thus, possible N loss occurred with N applied at-planting indicated by higher $VTNT_0$0-30 with N split-applied at the 90, 180, and 270 kg N ha^{-1} N rates (S = 2.1 to 35 mg kg^{-1}) than N applied at-planting (AP = 2.3 to 22 mg kg^{-1}). The VTN (averaged over productivity site and N rates 90 to 315 kg N ha^{-1}) was similar between timings, thus, perhaps reflects more N was available heading into grain fill with N split-applied than applied at-planting.

In 2016 at the low and high productivity sites in IN, PMN response to N rate was lower with N split-applied perhaps attributed to poor distribution of rainfall during the vegetative period (78), especially ten days before and after N was split-applied

($AWDR_{10dBASN}$ = 9) compared to 2014 (239 and 118) and 2015 (143 and 5, respectively). This possibly reduced N uptake indicated by higher $VTNT_0$0-60 across the 90, 180, and 270 kg N ha^{-1} (L [10.3 to 54.3 mg kg^{-1}] and H [4.5 to 28.5 mg kg^{-1}]) and reduced rate of N uptake at VT (L [0.048 kg N ha^{-1}] and H [0.114 kg N ha^{-1}]) with N split-applied than at-planting ($VTNT_0$0-60: L [11.9 to 34.0 mg kg^{-1}] and H [4.1 to 14.9 mg kg^{-1}] and VTN: L [0.156 kg N ha^{-1}] and H [0.142 kg N ha^{-1}]; data not shown). Higher PMN at the low productivity site with N applied at-planting than the high productivity site was perhaps attributed to better soil drainage indicated by SSURGO drainage classification of well drained in the low productivity site (Tracy soil series) and very poorly drained in the high productivity site (Sebewa soil series). Thus, could have led to faster soil warm up and increased N uptake in the low productivity site compared to the high productivity site indicated by higher VTN with N applied at-planting in the low productivity site (166 to 215 kg ha^{-1}) than both timing in the high productivity site (AP = 156 to 185 kg ha^{-1} and S = 138 to 170 kg ha^{-1}).

2.4.1.3 Internal Nitrogen Efficiency

In 2014 IN at the low and high productivity sites, IE (averaged over timing) response to N rate was quadratic. In contrast, the high productivity site in 2016, IE response to N rate was linear. The differences in IE response to increasing N rates in 2014 (low and high productivity sites) and 2016 (high productivity site) were correlated with GDM quadratic (averaged over productivity site and timing) and PMN (Prod.*NR_L) linear response to N rates in 2014 and a linear response in GDM (Prod.*NR_L) and PMN (Prod*NR_L*T) in 2016. Thus, the rate of reduction in efficiency to converting N into GDM in 2014 was reduced at higher N rates, but in 2016 the rates of decrease were consistent at higher N rates.

In 2016 at the low productivity site, split-applied N caused no response in IE with higher N possibly attributed to water stress conditions observed prior to N split application ($AWDR_{Vege}$; [2014 = 239, 2015 = 143, and 2016 = 78], and $AWDR_{10BSN}$ [2014 = 105, 2015 = 2, and 2016 = 4]), which further reduced N availability with N split-applied (45 kg N ha^{-1} applied at-planting). This perhaps reduced the plants ability to recover after the N stress once N was added around V9±1 V-stage indicated by low VTN with split-applied N (157 kg ha^{-1}) compared to at-planting (171 kg ha^{-1}). At the high productivity site in 2016 IN, split-applied N had higher IE correlated with a 4.6% reduction in PMN and only 0.9% reduction in GDM compared to N applied at-planting. Other studies on N application timing effects on IE have shown mixed results, with some finding higher IE with planting-time N (Abbasi et al., 2012; Sainz Rozas et al., 2004), and others reporting higher IE with split-applied N (Randall et al., 1997). A meta-analysis of 51 N response studies noted less frequent rain events 15 days before and 30 days after sidedress (< 99) at 28 of the 51 studies decreased N uptake compared to more frequent rain events (> 99) at 23 of the 51 studies (Tremblay et al., 2012).

2.4.1.4 Site and Nitrogen Timing and Rate effects on Northern Corn Leaf Blight

In 2015, the distribution of rainfall (72) combined with moderate temperature (28°C) around VT ($AWDR_{2wkBAVT}$ and $HT_{2wkBAVT}$, respectively) and a susceptible hybrid favored NCLB development and, correlated with increased the loss of photosynthically active leaf area. I believe the loss of leaf area affected GDM, PMN, and IE response to N rate, timing, and productivity site.

The greater infection of NCLB in the high productivity site was correlated with higher plant N concentration (H = 16.1 vs. L = 15.5 g kg^{-1}) and lower plant biomass at VT (H = 10,067 vs. L = 11,568 kg DM ha^{-1}). The lower biomass in the high productivity site was correlated with greater concentration of N in the plant tissue indicated by higher plant N concentration (H = 16.1 vs. L = 15.5 g kg^{-1}) at VT. This was possibly influenced by poorer drainage in the high productivity site (Sebewa: SSURGO very poorly drained) compared to low productivity site (Tracy: SSURGO well drained) and excessive rainfall during the vegetative period (143). Several studies noted that higher leaf N concentration supported initial growth of obligate fungi such as NCLB (Neumann et al., 2004; Solomon et al., 2003; Walters and Bingham, 2007).

The differences in GDM, PMN, and IE between N application timing at the high productivity site was correlated with the greater loss of photosynthetically active leaf area coincided with higher NCLB infection with N applied at-planting (AP = 69% vs. S = 58% loss of leaf area). These reduction in GDM, PMN, and IE response to increasing N rates at the high productivity site with N applied at-planting was likely correlated with higher N concentration (AP = 18.7 vs S = 15.9 g kg^{-1}) and lower biomass (AP = 10,065 vs. S = 10,714 kg DM ha^{-1}) compared to split-applied N. Another study found contradictory results indicating timing of N (11 or 56 kg N ha^{-1} at planting plus 157 or 112 kg N ha^{-1} at sidedress) did not increase the corn plant suitability to NCLB (Bair, 1988). However, disease severity from NCLB increased with higher N rates (0, 123, 157, 191,225 kg N ha^{-1}) applied at sidedress indicated by greater loss of leaf area (14 to 63% loss of leaf area) at the R4 growth stage (dough).

2.4.2 Internal Nitrogen Efficiency and Components at the Economic Optimum Nitrogen Rate across Forty-Nine Site-Years

2.4.2.1 Grain Dry Matter

Across the two productivity sites and eight states over three years, 93% of GDM positive response to increasing N rates (0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) were quadratic-plateau. This type of response to increased N implies that environmental stresses other than insufficient N (perhaps rainfall, temperature, and soil properties) limited the corn plant's ability to further increase GDM. Indeed, during grain fill, greater rainfall (TR_{GF}) and increased adequate and well-distributed rainfall ($AWDR_{GF}$) were positively related to GDM_E and PMN_E.

Tremblay et al. (2012) noted the distribution of rainfall around sidedress (15 days before and 30 days after) and soil texture influenced GDM response to N rate. A combination effect between better distribution of rainfall around sidedress time and fine textured soil increased GDM 4.5-fold compared to fine texture or distribution of rainfall around sidedress alone across 51 N response studies. In our study, AWDR around at-planting ($AWDR_{10dBAPN}$) was weakly correlated to GDM_E and PMN_E, however, distribution of rainfall around split-applied N ($AWDR_{10BSN}$, $AWDR_{10ASN}$, and/or $AWDR_{10dBASN}$) and silt or sand content were not related with GDM_E ($p > 0.10$), except for clay content ($p \leq 0.10$).

In our study, timing affected GDM_E at 41% of all site-years, but one timing was not consistently better than the other. Another study found no difference in GDM between N timings ('at-planting' [168 kg N ha^{-1}] and split-applied N [112 kg N ha^{-1} applied at-planting and 56 kg N ha^{-1} at sidedress]) over a four year period ($p > 0.10$)

(Torbert et al., 2001). Differences in timing of N were shown in Sainz Rozas et al. (2004), who found that pre-plant N application produced greater GDM than split-applied N in years with more rainfall during early growth.

2.4.2.2 Physiological Maturity Total Plant Nitrogen Content

In our study, PMN increased quadratically with increasing N rates at 79% of all site-years and N application timings. Another study noted a quadratic response in PMN with increasing N rates (0 to 225 kg N ha^{-1} in 45 kg N ha^{-1} increments) for fields with or without rye cover crop across all sites and years (Pantoja et al., 2015). Several studies found similar response in PMN to higher N rates (Woli et al., 2016; Wortmann et al., 2011).

Across all three years, approximately 61% of the PMN_E varied between 178 to 243 kg N ha^{-1} with an average of 208 kg N ha^{-1}. Other studies (n = 19 site-years) found PMN_E varied from 159 to 244 kg N ha^{-1} with an average of 204 kg N ha^{-1} (Halvorson and Bartolo, 2014; Kovács et al., 2015; Pantoja et al., 2015; Woli et al., 2016). In our study, the PMN_E was unaffected by timing at 51% of all site-years. When timing did affect PMN_E, 70% of PMN_E was higher with N applied at-planting and 69% of the 70% of higher PMN_E were correlated with greater SDM_E. The remaining 1% of the 70% of higher PMN_E with N applied at-planting was correlated with higher SNC_E or combination of higher SNC_E and SDM_E. Another study found N applied prior to planting (0 to 168 kg N ha^{-1} in 56 kg N ha^{-1} increments) produced higher PMN_E (225 kg N ha^{-1}) than sidedress N (214 kg N ha^{-1}) (Bigeriego et al., 1979). This was correlated with higher SDM_E with early N application (10,451 kg ha^{-1}) than N applied at sidedress (9,916 kg ha^{-1}). In our study, application of N at-planting increased N uptake compared to split-applied N indicated by higher VTN at the EONR at 94% of all the site-years where PMN_E was higher with N applied at-planting ($p \leq 0.10$; data not shown). This could be a result of withholding N until V9±1 stage, which may have reduced the corn plants ability to take up N during the start of rapid growth around V5±1 stage.

2.4.2.3 Grain Nitrogen Concentration

In our study, GNC increased quadratically with increased N rates at 52% of all site-years and N application timings, while 44% of all site-years and N application timings continued to increase with increasing N rates (linear). Another study noted protein concentration (approx. 160 g kg^{-1} N), increased up to 201 kg N ha^{-1} N rate but no further with higher N rates (268 and 402 kg N ha^{-1}) (Tsai et al., 1992).

Across all three years, about 82% of the variation in GNC_E occurred between 10.8 to 13.1 g kg^{-1} with an average of 11.8 g kg^{-1}. Other studies noted GNC in current hybrids was approximately 11.9 to 12.3 g kg^{-1} (Ciampitti and Vyn, 2012; Woli et al., 2016). Timing did not affect GNC_E 55% of the time in our study, but site-years where timing did affect GNC_E, 52% were higher with split-applied N and 48% were higher with N applied at-planting. Thus, timing had no consistent effect on GNC_E. Another study found no difference in N timing (0 to 168 kg N ha^{-1} in 56 kg N ha^{-1} increments, either all applied at-planting or at sidedress) for GNC_E (Bigeriego et al., 1979).

2.4.2.4 Stover Dry Matter

Stover dry matter increased with higher N rates linearly, quadratically or quadratic-plateau 19%, 39% and 27%, respectively, of all site-years and N application timings. Another study found SDM responded quadratically or quadratic-plateau to increased N rates (0 to 225 kg N ha^{-1} in 45 kg N ha^{-1} increments) at 3 and 2, respectively, of the six years (Derby et al., 2005).

Nitrogen application timing did not affect SDM_E at 51% of all site-years. When SDM_E was affected by timing, N applied at-planting correlated with greater SDM_E at 92% of these site-years. Nitrogen applied at-planting increased the amount of N accumulated during vegetative period indicated by higher SDM_E at VT at 80% of all the site-years where SDM_E was higher with N applied at-planting ($p \leq 0.10$; data not shown). The remaining five site-years SDM_E at VT were not different between N application timing ($p > 0.10$; data not shown). Another study noted higher SDM_E with N supplied (0 to 168 kg N ha^{-1} in 56 kg N ha^{-1} increments) early in the growing season (all pre-plant SDM_E = 10,451 kg ha^{-1}) compared to later (all at sidedress SDM_E = 9,916 kg ha^{-1}) (Bigeriego et al., 1979).

2.4.2.5 Stover Nitrogen Concentration

The SNC increased linearly with higher N rates at 73% of all site-years and N application timings. This was due to a plateauing of SDM and GDM, thus, resulting in the storage of N without a continuation in the increase in GDM. Another study showed higher stalk N accumulation beyond the optimum N rate for GDM indicated by linear response in stalk N with higher N rates (2009 [0, 30, 59, 88, 118, and 147 kg N ha^{-1}], 2010, and 2011 [0, 112, 168, 224, 280, and 336 kg N ha^{-1}]) in each of the three years (Halvorson and Bartolo, 2014). Other studies noted similar response in stover N accumulation to higher N rates that increased beyond the optimum N rate for SDM and GDM (Kovács et al., 2015; Niaz et al., 2015).

Across all three years, about 58% of the variation in SNC_E was between 6.7 to 9.1 g kg^{-1} with an average of 8.1 g kg^{-1}. Timing of N application did not affect SNC_E at 59% of all site-years. When timing did affect SNC_E, it was not consistently higher for one N application timing (AP = 45% and S = 55%). A study found no difference between N timings (0 to 180 kg N ha^{-1} in 45 kg N ha^{-1} increments ‘all at-planting’ and split-applied 35 kg N ha^{-1} at-planting with remaining applied at V6) for SNC (Liu and Wiatrak, 2011).

2.4.2.6 Internal Nitrogen Efficiency

Internal N efficiency decreased with increasing N rates either linearly or quadratically at 64% or 26% of all site-years and N application timings, respectively. Six percent of all site-years and N application timings resulted in an increase in IE with increasing N rate. The rate of decrease varied from -0.087 to -0.016 kg GDM kg^{-1} N with an average of -0.046 kg GDM kg^{-1} N for linear response and -0.156 to -0.071 kg GDM kg^{-1} N with an average of -0.115 kg GDM kg^{-1} N for quadratic response. Other studies found IE decreased with increasing N rates linearly or quadratically 75% or 15% of all site-years. The average rate of change varied between -0.098 and -0.020 kg GDM kg^{-1} N or -1.361 to -0.196 kg GDM kg^{-1}, respectively (Bigeriego et al., 1979; Kamprath et al., 1982; Huggins and Pan, 1993; Tobert et al., 2001; Wortmann et al., 2011).

In our study, average IE_E (across all site-years) was 53 kg GDM kg^{-1} N, with 79% of the variation in IE_E between 46 and 60 kg GDM kg^{-1} N. Wortmann et al. (2011) found similar IE_E across three crop rotations (continuous corn, corn-dry bean, and corn-soybean rotation) in Nebraska. The IE_E varied from 48 to 56 kg GDM kg^{-1} N with an average of 51 kg GDM kg^{-1} N. Our study and that of Wortmann et al. (2011) show IE_E values fall within close approximation of IE_E values of hybrids within this decade (47 to 56 kg GDM kg^{-1} N) (Ciampitti and Vyn, 2012; Woli et al., 2016). This is in contrast to Stanford (1966), which concluded IE was approximately 47 kg GDM kg^{-1} and was relatively unaffected by genotype or the environment.

In our study, N timing did not affect IE_E at 51% of all site-years due to no differences between timings for GDM_E and PMN_E (50% of site-years where timing was non-significant). The remaining 50% of these site's where timing was non-significant had differences in GDM_E and/or PMN_E between timings but were not enough to cause differences in timing for IE_E. Other studies noted IE did not vary between timings because GDM and PMN were unaffected by N timing (at-planting [168 kg N ha^{-1}] or split-applied [112 kg N ha^{-1} at-planting plus 56 kg N ha^{-1} at sidedress]) (Torbert et al., 2001). Other studies found differences between timing for PMN and GDM, but they did not result in differences in IE (Fox and Bandel, 1986; Sainz Rozas et al., 2004).

When N timing did affect IE_E in our study, 70% were higher with split-applied N and 69% of the 70% of higher IE_E with split-applied N was correlated with lower PMN_E. The remaining IE_E was correlated with higher GDM_E (13%) or a combination of GDM_E and PMN_E (19%). Another study found higher IE_E with sidedress N (52 kg GDM kg^{-1} N) compared to at-planting N (48 kg GDM kg^{-1} N) due to lower PMN_E and higher GDM_E for sidedress N (PMN_E = 214 kg ha^{-1} and GDM_E = 11,195 kg ha^{-1}) than at-planting (PMN_E = 225 kg ha^{-1} and GDM_E = 10,838 kg ha^{-1}) (Bigeriego et al., 1979). In our study, N applied at-planting increased the amount of N taken up during vegetative growth indicated by higher VTN at the EONR at 69% of all site-years where IE_E was highest with N applied at-planting (data not shown). The remaining 31% of the site-years where IE_E was highest with N applied at-planting showed no difference in VTN at EONR between timings. Approximately 65% of total N is accumulated by VT/R1 (Abendroth et al., 2011; Bender et al., 2013; Doerge et al., 1991; Scharf and Lory, 2006), thus, the earlier supply of N (at-planting) increased plant uptake of N due to more time to accumulate N and better distribution of rainfall during vegetative period compared to N split-applied (N applied at V9±1 V-stage) indicated by higher VTN at EONR and lower

IE_E at locations where $AWDR_{Vege}$ (105 to 291) was better than $AWDR_{GF}$ (31 to 206). This occurred at 63% of the site-years where VTN at EONR was higher and IE_E was lower for N applied at-planting compared to N split-applied. Several studies showed N applied at pre-plant or at-planting increased N uptake compared to split or sidedress application due to drier soil conditions later in the growing season (Bigeriego et al., 1979; Sela et al., 2016; Kovács et al., 2015).

The negative relationship between PMN_E, SDM_E, SNC_E, and GNC_E with IE_E indicates the plant continued to accumulate N even though GDM plateaued. Thus, the concentration of the grain and remaining tissue increased with higher N rates above the plateau. Data combined from Halvorson and Bartolo (2014) and Al-Kaisi and Kwaw-Mensah (2007) noted stover and total plant N uptake increased with higher N rates while GDM plateau at higher N rates, thus, IE_E was negatively related to PMN_E ($p \leq 0.10$, r = -0.71) and SNC_E (r = -0.91). Several studies with rice (*Oryza sativa* L.) also found higher GNC and SNC were related to less conversion of N into GDM (Inthapanya et al., 2000; Koutroubas and Ntanos, 2003; Singh et al., 1998).

2.4.3 Weather Factor Relationship with Internal Nitrogen Efficiency Availability

2.4.3.1 Total Rainfall and Abundant and Well-Distributed Rainfall

The amount of rainfall determined at different periods of the growing season were not related to IE_E. However, $AWDR_{2wkAVT}$ was negatively related to IE_E across all site-years possibly attributed to increased N uptake at sites where rainfall was better distributed during the two week period after VT indicated by $AWDR_{2wkAVT}$ positive relationship with PMN_E, SNC_E, and SDM_E. The $AWDR_{2wkBAVT}$ was not related with IE_E across all site-years possibly a result of contrasting relationships between $AWDR_{2wkBAVT}$ and IE_E in two of the three years. The contrast relationships in 2014 and 2016 were likely a result of differences in the average $AWDR_{2wkBAVT}$ in individual years (2014: 22 and 2016: 69). This possibly influenced the amount of N taken up indicated by $AWDR_{2wkBAVT}$ positive relationship with $VTNT_0$ (at all depths) and negative relationship with SNC_E in 2014. In contrast, $AWDR_{2wkBAVT}$ in 2016 was negatively related with $VTNT_0$ (at all depths) and positively with SNC_E. Thus, the $AWDR_{2wkBAVT}$ perhaps reduced and increased N uptake, which led to a positive and negative relationship with IE_E in 2014 and 2016, respectively.

2.4.3.2 Temperature

Across all site-years, changes in mean high temperatures were not consistently related to IE_E, which was possibly a result of better distribution of rainfall influencing mean high temperatures relationship with N uptake. For example, HT_{2wkAVT} and HT_{GF} average temperature slightly increased from 2014 to 2016 (HT_{2wkAVT} [2014 = 28, 2015 = 29, and 2016 = 30°C] and HT_{GF} [2014 = 27, 2015 = 28, and 2016 = 29°C]), however, average $AWDR_{2wkAVT}$ and $AWDR_{GF}$ were different ($AWDR_{2wkAVT}$ [2014 = 10, 2015 = 14, and 2016 = 23] and $AWDR_{GF}$ [2014 = 119, 2015 = 89, and 2016 = 178]). Thus, $AWDR_{2wkAVT}$ and $AWDR_{GF}$ in 2014 and 2016 were likely able to compensate for the temperature effect on the plant by maintaining N uptake indicated by HT_{2wkAVT} and HT_{GF} positive relationship with PMN_E in 2014 and 2016 (HT_{2wkAVT} [2014 r = 0.46 and 2016, r = 0.67] and HT_{GF} [2014, r = 0.58 and 2016, r = 0.48]). In contrast, HT_{2wkAVT} and HT_{GF} in 2015 were negatively related with PMN_E (HT_{2wkAVT} [2015, r = -0.43] and HT_{GF} [2015, r = -0.37]), thus, $AWDR_{2wkAVT}$ and $AWDR_{GF}$ were likely not able to compensate for the temperature effect on the uptake of N. Research has shown, reduced soil moisture during periods of higher temperatures decreases photosynthesis, which lowers the uptake of N (Flexas et al., 2005; Gratani et al., 2008; Reichstein et al., 2002). Another study noted higher temperature 30 days before or ten days after sidedress increase N uptake, especially when there was higher distribution of rainfall (Tremblay et al., 2012).

2.4.4 Soil Properties Relationship with Internal Nitrogen Efficiency

2.4.4.1 Soil Texture

Soil textures (silt and sand content) across all productivity sites and eight states over three years were only weakly correlated with IE_E, even though differences in soil texture influence N availability and loss (Christensen and Olesen, 1998; Tremblay et al., 2012). This weak relationship was possibly attributed to the poor relationship between silt and sand content with N uptake at VT (VTN_0 and VTN_{45}) and no relationship with N uptake at maturity (PMN_0 and PMN_{45}). Clay content did not relate to IE_E or VTN and PMN at 0 and 45 kg N ha^{-1} across all years or for any individual years.

2.4.4.2 Organic matter content

Overall, the concentration of OM in the Ap horizon (OM_2, OM_3, and ROM) was not related to IE_E, even though past studies noted its impact on N mineralization and N availability (Shaver, 2014; Akintoye et al., 1999; Griffin, 2008). Since IE in our study was determined at the EONR, it could be insensitive to the amount of N mineralized or available.

2.4.4.3 Plant Available Water Content

In general, PAWC (at each depth and averaged over each depth) were negatively related with IE_E across all site-years. This was likely attributed to PAWC (PAWC0-30, PAWC30-60, PAWC60-90, and PAWC0-90) positive correlation with SDM (SDM_0, SDM_{45}, and SDM_E). The increase in the amount of residual and mineralized N taken up (VTN_0 and VTN_{45}) was correlated with sites where PAWC0-30 was greater. However, PAWC at the 30-60, 60-90 cm, and averaged over each depth (0-90 cm depth) were not related with VTN (VTN_0 and VTN_{45}). As a result of PAWC (PAWC0-30, PAWC30-60, PAWC60-90, and PAWC0-90) relationship with greater retention of SDM (SDM_0, SDM_{45}, and SDM_E) and PAWC0-30 with VTN (VTN_0 and VTN_{45}) likely influenced PAWC negative relationship with IE_E.

Several studies noted soil texture, which is related to PAWC, influenced N uptake with fine texture soils increased N uptake than medium textured soils due to greater water holding capacity with fine texture soil (Scharf et al., 2005; Tremblay et al., 2012). In another study, soils with higher electrical conductivity, which is correlated with PAWC, resulted in greater plant response to N compared to soils with lower electrical conductivity (Tremblay et al., 2011). Another study found lower IE_E (48 kg GDM kg^{-1} N) on fine textured soil (clay loam) than on a coarser-textured soil (silt loam) (52 kg GDM kg^{-1} N) due to increase in GDM_E (clay loam 5,672 kg GDM ha^{-1} vs silt loam 8,136 kg GDM ha^{-1}), but not SDM_E (Jokela and Randall, 1989).

2.4.5 Residual Soil Nitrate

Soil NO_3-N at PPNT (at 0-30 and 30-60 cm depth) was weakly related with IE_E across all three years ($p \leq 0.10$, r = -0.19 and -0.20, respectively). This measurement possibly reflects the soil capacity to mineralize N, however, N mineralization prior to planting is often low due to wet and cool environment conditions, thus, not reflecting the full mineralization potential of a soil. Later measurements of soil NO_3-N ($PSNT_0$, $PSNT_{45}$, and $VTNT_0$ at all depths) were not related to IE_E across all three years.

2.4.6 Crop Reflectance

In general, NDVI and NDRE and its components [red (R), red edge (RE), and near reflectance (NIR)] of the non-fertilized or 45 kg N ha^{-1} treatments were weakly or not correlated with IE_E across all site-years. Analysis of data combined from several studies noted no relationship between NDVI ($NDVI_0$ and $NDVI_{45}$) with IE_E (p >0.10) (Pantoja et al., 2015; Woli et al., 2016). However, in our study sufficiency and simple ratios indices for both NDVI and NDRE at the non-fertilized and 45 kg N ha^{-1} treatments were negatively related with IE_E across all site-years. This was perhaps attributed to sufficiency indices and simple ratios (for both NDVI and NDRE) reflecting N accumulation at the time of sensing (V9±1 V-stage) with plant biomass at VT (VTN_0 and VTN_{45}), maturity (PMN_0 and PMN_{45}, and PMN_E), and GNC_E. Several studies found sufficiency indices and simple ratios were correlated with biomass and N uptake (Roberts, 2006; Stevens, 2014) and were better correlated with these factors than NDVI and NDRE (Solari et al., 2008). In our study, the relationship between sufficiency indices and simple ratios (for both NDVI and NDRE of the non-fertilized and 45 kg N ha^{-1} treatments) with IE_E occurred in 2014 and 2015, but not in 2016. The lack of a relationship in 2016 was likely a result of no relationship between sufficiency and simple ratios indices with PMN_E, which did occur in 2014 and 2015.

2.4.7 Plant Variables Relationship with Internal Nitrogen Efficiency

2.4.7.1 Plant Nitrogen Content at Tasseling and Physiological Maturity

In our study, the amount of residual N taken up by the plant at tasseling (VTN_0 and VTN_{45}) and maturity (PMN_0 and PMN_{45}) varied from 32 to 210 kg N ha^{-1} and 36 to

265 kg N ha^{-1}, respectively, likely a result of differences in the environmental conditions across the eight states. Nitrogen uptake at VT and maturity of the non-fertilized and 45 kg N ha^{-1} treatments were negatively related to IE_E across all site-years (VTN [r = -0.42 and -0.50] and PMN [r = -0.28 and -0.35, respectively]). This was indicated by VTN and PMN of the non-fertilized and 45 kg N ha^{-1} treatments negative relationship with several factors that reduced IE_E - PMN_E, SNC_E, and GNC_E. A separate analysis of the data from the literature (Al-Kaisi and Kwaw-Mensah, 2007; Woli et al., 2016) were used due to the presentation of VTN compared to other studies (Bigeriego et al., 1979; Derby et al., 2005; Halvorson and Bartolo, 2014; Jokela and Randall, 1989; Kovács et al., 2015; Menelik et al., 1994; Sindelar et al., 2015; Torbert et al., 2001; Woli et al., 2016) that did not present VTN. These two studies also found IE_E was negatively related to VTN ($p \leq 0.10$, VTN_0, r = -0.70 and VTN_{45}, -0.74) and PMN (PMN_0, r = -0.85 and PMN_{45}, -0.90) due to plant N content at VT or physiological maturity fertilized with non-fertilized or 45 kg N ha^{-1} being positively and well correlated with PMN_E ($p \leq 0.10$, $0.73 \leq r \leq 0.97$). These studies noted IE_E, VTN, and PMN of the non-fertilized and 45 kg N ha^{-1} treatments varied from 36 to 65 kg GDM kg^{-1} N, 51 to 166 kg N ha^{-1}, and 79 to 195 kg N ha^{-1}, respectively.

Environmental factors promoting greater N mineralization and uptake of residual N increased VTN (VTN_0 and VTN_{45}) and PMN (PMN_0 and PMN_{45}) indicated by PPNT0-60*Silt Content*$HT_{2wkBAVT}$ and PAWC0-30 positive relationship with VTN (VTN_0 and VTN_{45}) and PMN (PMN_0 and PMN_{45}). Another study noted soil texture, heat units (30 days before and 15 days after sidedress), and distribution of rainfall (15 days before and 30 days after sidedress) effect on N availability and uptake (Tremblay et al., 2012). Fine textured soils increased N uptake more compared to medium textured soils. Higher temperature 30 days before and 15 days after sidedress increase N uptake, especially, when there was higher distribution of rainfall. In another study, electrical conductivity was correlated with PAWC, thus, soils with higher electrical conductivity resulted in greater response to N compared to soils with lower electrical conductivity (Tremblay et al., 2011).

2.4.7.1.1 Harvest Index

In our study, HI (HI_0 and HI_{45}) across all site-years varied from 0.30 to 0.68. Previous studies noted similar variation in HI at non-fertilized or 45 kg N ha^{-1} (0.29 to 0.68) compared to our study (Burzaco et al., 2014; Haegele et al., 2013; Halvorson and Bartolo, 2014; Menelik et al., 1994; Sindelar et al., 2015; Tobert et al., 2001). In our study, these ranges in HI (HI_0 and HI_{45}) were likely a result of variations in environmental conditions across the eight states. Harvest index (HI_0 and HI_{45}) was positively related with IE_E possibly a result of the negative relationship of HI (HI_0 and HI_{45}) with SDM_E. A separate analysis of the data collected from several corn fertilizer response studies (n = 44 site-years) show HI_0 and HI_{45} were positively related to IE_E ($p \leq 0.10$, r = 0.60 and 0.61, respectively) and negatively related with SDM_E (r = -0.52 and -0.56, respectively) (Bigeriego et al., 1979; Derby et al., 2005; Halvorson and Bartolo, 2014; Jokela and Randall, 1989; Kovács et al., 2015; Menelik et al.,1994; Sindelar et al., 2015; Torbert et al., 2001; Woli et al., 2016). Al-Kaisi and Kwaw-Mensah (2007), Halvorson and Reule (2006), and Pantoja et al. (2015) were not used in the analysis due to no prestation of SDM. In our study, sites with higher PAWC0-30 were correlated with lower HI (HI_0 and HI_{45}) likely a result of increased SDM_E indicated by HI_0 and HI_{45} negative relationship with PAWC0-30 (r = -0.24 and r = -0.24, respectively) and SDM_E positive relationship with PAWC0-30 (r = 0.30). Tremblay et al. (2011) found increased biomass, indicated by average NDVI, in locations with higher soil electrical conductivity, which was related with higher PAWC.

2.4.7.1.2 Nitrogen Harvest Index

In our study, the variation in NHI_0 and NHI_{45} across all site-years (0.40 to 0.72) was close to the variation found in past studies (NHI_0 and NHI_{45} = 0.34 to 0.81) (Al-Kaisi and Kwaw-Mensah, 2007; Bigeriego et al., 1979; Derby et al., 2005; Halvorson and Bartolo., 2014; Halvorson and Reule, 2006; Jokela and Randall, 1989; Kovács et al., 2015; Menelik et al.,1994; Pantoja et al., 2015; Torbert et al., 2001). In our study, NHI (NHI_0 and NHI_{45}) was positively related with IE_E ($p \leq 0.10$, r = 0.36 and 0.47, respectively) across all site-years was likely a result of the negative relationships of NHI_0 and NHI_{45} with PMN_E ($p \leq 0.10$, r = -0.32 and -0.34, respectively), SNC_E (r = -0.35 and -

0.45) and SDM_E (r = -0.63 and -0.62). A separate analysis of the data from other N response studies (n = 55 site-years) also showed NHI at the 0 and 45 kg N ha^{-1} treatments were positively related to IE_E ($p \leq 0.10$, r = 0.45 and 0.61, respectively) due to NHI (NHI_0 and NHI_{45}) negative relationship with SNC_E (r = -0.61 and -0.73) and SDM_E ($p \leq 0.10$, r = -0.64 and -0.66, respectively), but not with PMN_E ($p > 0.10$) (Al-Kaisi and Kwaw-Mensah, 2007; Bigeriego et al., 1979; Derby et al., 2005; Halvorson and Bartolo, 2014; Halvorson and Reule, 2006; Jokela and Randall, 1989; Kovács et al., 2015; Menelik et al.,1994; Pantoja et al., 2015; Torbert et al., 2001). Sindelar et al. (2015) and Woli et al. (2016) studies were not used in the analysis due to no presentation of grain N content.

Environmental factors that correlated with improved NHI (NHI_0 and NHI_{45}) were sites with lower PAWC indicated by the negative relationship of NHI (NHI_0 and NHI_{45}) with higher PAWC0-30 (r ≤ -0.39). Sites with higher PAWC0-30 reflected conditions better for N uptake indicated by PAWC0-30 positive relationship with VTN and PMN (at 0 and 45 kg N ha^{-1}). In another study, soils with higher PAWC (estimated by higher electrical conductivity) resulted in greater biomass, indicated by higher averaged NDVI, compared to soils with lower PAWC (Tremblay et al., 2011).

2.4.7.1.3 Net Change in Stover N

Environmental conditions conducive for remobilization of stover N to the grain and/or N loss to the environment were positively related to IE_E (ΔNCS_0, r = 0.23 and ΔNCS_{45}, r = 0.23). This outcome was likely a result of the ΔNCS (ΔNCS_0 and ΔNCS_{45}) negative relationship with SNC_E and GNC_E. Al-Kaisi and Kwaw-Mensah (2007) found higher ΔNCS_{45} was positively related to IE_E ($p \leq 0.10$, r = 0.68), but was not related with ΔNCS_0 ($p > 0.10$). In our study, locations with higher PAWC0-30 were negatively related with ΔNCS (ΔNCS_0 and ΔNCS_{45}) possibly a result of increased uptake of residual N indicated by PAWC0-30 positive relationship with VTN (VTN_0 and VTN_{45}) and PMN (PMN_0 and PMN_{45}) and ΔNCS (ΔNCS_0 and ΔNCS_{45}) negative relationship with VTN (VTN_0 and VTN_{45}), PMN (PMN_0 and PMN_{45}), and SNC_E.

2.4.8 Variables at the 45 kg N ha^{-1} Rate

In general, the supply of 45 kg N ha^{-1} at planting improved the relationship between plant, soil, and crop reflectance variables with IE_E. When mineralization of N does not meet the plant N requirement, the addition of a low amount of N (45 kg N ha^{-1}) may reduce the plant dependence on mineralization of N early in plant growth. This added N fertilizer increased plant N content at VT from 92 kg N ha^{-1} (VTN_0: varied between 32 to 160 kg N ha^{-1}) to 122 kg N ha^{-1} (VTN_{45}: varied between 36 to 210 kg N ha^{-1}). Enhanced plant N content with 45 kg N ha^{-1} at planting was also seen at physiological maturity with 109 kg N ha^{-1} (varied between 36 to 243 kg N ha^{-1}) and 141 kg N ha^{-1} (varied between 44 to 265 kg N ha^{-1}) at the non-fertilized (PMN_0) and 45 kg N ha^{-1} (PMN_{45}), respectively. Al-Kaisi and Kwaw-Mensah (2007) and Woli et al (2016) found higher average plant N content at VT and maturity with 45 kg N ha^{-1} (113 and 156 kg N ha^{-1}, respectively) compared to non-fertilized treatment (74 and 116 kg N ha^{-1}).

2.4.9 Predictive Models for Internal N Efficiency

2.4.9.1 Prediction of Internal N Efficiency Prior to Planting

The ability to predict IE_E, rather than use a static value of IE_E, should improve yield-goal based models for predicting EONR (Morris et al., 2018). At-planting variables, soil texture (clay, silt, and sand), cation exchange capacity (CEC), total carbon, total organic carbon, total inorganic carbon (TOC), OM_2 (TOC), OM_3 (TGA), pH-water (pH_w), pH-salt (pH_s), bulk density, PAWC (at the 0-30, 30-60, 30-90 cm depths, and averaged over each depth 0-90), and PPNT (at the 0-30, 30-60 cm depth, and averaged over depths 0-60 cm), were available for predicting IE_E. Of these variables, only PAWC0-30 and PPNT0-60 N were related to IE_E (negatively); explaining just 19% (n = 88 site-years) of the variation in IE_E (Table 34). The PAWC0-30 and PPNT0-60 showed a positive relationship with VTN_0 and VTN_{45} which were among the most important factors for predicting IE_E. Increased VTN_0 and VTN_{45} were negatively related to IE_E. Greater water holding capacity and initial soil NO_3-N at the beginning of the season likely reflect better conditions for soil N mineralization and perhaps continued N uptake during the grain filling period. Some studies (Tremblay et al., 2012; Zhu et al., 2009) noted that greater PAWC in fine-textured soils compared to soils with coarse-texture increased soil N availability and N uptake. Another study (Hassink, 1994) found greater N mineralization rates in the top 10 cm of grassland soils that were loamy (2.42 mg kg^{-1} d^{-1}) compared to those that were sandy (0.60 mg kg^{-1} d^{-1}). In our study, silt and sand concentration were positively and negatively correlated, respectively, with VTN_0, VTN_{45}, and PAWC0-30 across all site-years.

2.4.9.2 Prediction of Internal N Efficiency Prior to Sidedress

Variables found predictive of IE_E in the prior to planting model, PAWC0-30 and PPNT0-60, were also found predictive at the time of sidedress (V9±1 V-stage) when additional variables ($PSNT_0$ and $PSNT_{45}$ [at the 0-30, 30-60, and averaged over each depth 0-60], rainfall and abundant and well-distributed rainfall ten days before and/or after N applied at-planting, crop reflectances [R, NIR, RE, NDVI, and NDRE at the 0 and 45 kg N ha^{-1}], and sufficiency indices) were considered. Of these additional variables, $NDVI_{45}$225, OM_3, CEC, $PSNT_{45}$0-30, $NDRE_0$, and pH_s were found predictive of IE_E (Table 34). This model explained 47% (n = 84 site-years) of the variation in IE_E. The $NDVI_{45}$225 was a good predictor of VTN_0 (r = 0.52) and VTN_{45} (r = 0.59), and perhaps led to the negative relationship with IE_E because of NDVI indirect measurement of plant biomass and chlorophyll content (Sharma et al., 2015; Torino et al., 2014). The remaining variables (OM_3, CEC, $PSNT_{45}$0-30, $NDRE_0$, and pH_s) contributed 27% of variation in IE_E with none exceeding partial R^2 values of 0.06. Several of these variables ($NDVI_{45}$225, $PSNT_{45}$0-30, and $NDRE_0$) possible indicated N uptake or N mineralization at VT indicated by VTN_0 and VTN_{45} positively related with $NDVI_{45}$225 (r = 0.52 and 0.59), $PSNT_{45}$0-30 (r = 0.40 and 0.28), and $NDRE_0$ (r = 0.25 and 0.42). The remaining variables (OM_3, CEC, and pH_s) possible indicated N mineralization at VT indicated by $VTNT_0$30-60 and $VTNT_0$0-60 positive relationship with OM_3 (r = 0.30 and 0.21), CEC (r = 0.27 and 0.29), and pH_s (r = 0.24 and 0.33), but these variables were not related with VTN_0 or VTN_{45} ($p > 0.10$).

2.4.9.3 Prediction of Internal N Efficiency Prior to Tasseling

All of the variables prior to V9 plus rainfall and abundant and well-distributed rainfall ten days before and/or after split-applied, which were collected between V9 and

VT, were evaluated as predictors of IE_E prior to VT. Of the additional variables examined, the distribution of rainfall ten days before and after the split-N application at V9 ($AWDR_{10BSN}$ and $AWDR_{10ASN}$), $NDRE_{45}$, and pH_w were added to the model and improved the prediction of IE_E (Table 34). The complete model explained 62% (n = 84 site-years) of the variation in IE_E and none of the added variables ($AWDR_{10BSN}$, $AWDR_{10ASN}$, $NDRE_{45}$, and pH_w) exceeded a partial R^2 values of 0.07. The $AWDR_{10BSN}$ and $NDRE_{45}$ improved the predication of VTN_0 and VTN_{45}, thus improved the predication of IE_E. The other variables were not related to VTN_0 or VTN_{45} ($p > 0.10$).

2.4.9.4 Nitrogen Recommendation Model for Rescue Application

The use of a rescue N application (VT or later) could be used when environmental conditions prevented earlier N applications. All of the variables collected up to VT, were evaluated as predictors of IE_E. Of the additional variables examined, VTN_{45} was added to the model and accounted for 34% of variation in IE_E, which was negatively related to IE_E. Overall the model explained 54% (n = 70 site-years) of the variation in IE_E. Plant N content at VT accounted for a large portion of the variation in IE_E, since around 65% of the total plant N is accumulated by VT/R1 (Abendroth et al., 2011; Bender et al., 2013; Doerge et al., 1991; Scharf and Lory, 2006), thus, providing a closer estimate of the amount of plant N content at maturity. Greater amounts of plant N (PMN_0, PMN_{45}, or PMN_E) at maturity was negatively related to IE_E. A separate analysis of the data from several other studies (n = 11 site-years) found IE_E was negatively related to VTN and PMN of the non-fertilized ($p \leq 0.10$, r = -0.70 and -0.85, respectively) and 45 kg N ha^{-1} N treatments (r = -0.74 and -0.90, respectively) (Al-Kaisi and Kwaw-Mensah, 2007; Woli et al., 2016). The next variable added into the model was PAWC60-90 which predicted 11% of the variation in IE_E. Environments with higher PAWC60-90 may have improved the accumulation of SDM indicated by PAWC60-90 positive relationship with SDM_E, thus was negatively related to IE_E. The next three variables included in the model were in the order of OM_2, clay, and $AWDR_{10ASN}$, which accounted for 13% of the variation in IE_E with none exceeding a partial R^2 value of 0.05.

2.4.10 Hybrids

In our study, the variation in IE_E across multiple environments for a specific hybrid was similar to the overall variation (39 to 73 kg GDM kg^{-1} N) and average across all hybrids (54 kg GDM kg^{-1} N). There was not a clear difference in the average IE_E between hybrids as indicated by overlapping standard deviations. Another study noted no differences in IE among twelve hybrids which varied from 44 to 68 kg GDM kg^{-1} N across water (deficit and adequate) and N treatments (0 and 200 kg N ha^{-1}) (O'Neill et al., 2004). Another study found no differences in IE among hybrids selected under high (25 hybrids) and low N rates (24 hybrids), however, variations were found across four locations (38 to 57 kg grain yield kg^{-1} N) (Presterl et al., 2002). This study indicated variations in environments influenced the plant efficiency to convert stored N into GDM. In contrast, one study found three open pollinated hybrids differed over a narrow range of IE (48 to 53 kg GDM kg^{-1} N with an average 52 kg GDM kg^{-1} N) due to difference in number of ears per plant (Kamprath et al., 1982). In our study, there did appear to be no difference between hybrids, however, the data does not allow this conclusion to be made, since the same hybrids were not used in consecutive years and across each location.

2.5 Conclusions

The first objective was to assess IE and its components response to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments), productivity site (high and low), and/or timing (all 'at-planting' and 45 kg N ha^{-1} at-planting with the remainder split-applied at V9± 1 V-stage) across three years in IN. However, there was no consistent interaction between N rate, productivity site, and/or timing for IE. This was perhaps a result of weather and environmental factors influence on the uptake and retention of N at maturity. For example, in 2015 higher IE at the high productivity site with N applied at-planting was correlated with lower PMN influenced by greater infection of NCLB indicated by higher amount of loss of photosynthically active leaf area compared to N split-applied (AP = 69% vs. S = 58% loss of leaf area). In 2016 at the high productivity site with split-applied N, IE was improved likely by a 4.6% reduction in PMN and only a 0.9% reduction in GDM compared to at-planting N application.

The second objective was to assess IE response to N rate (0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) and its relationship with its components at the EONR (GDM_E, GNC_E, PMN_E, SDM_E, and SNC_E) across eight states, productivity sites (high and low based on historical data), and N application timing over three years. Internal N efficiency decreased linearly 64% of all the site-years and N application timings at an average rate of -0.046 kg GDM kg^{-1} N. The average linear rate of decrease in IE_E was similar to other studies (-0.098 and -0.020 kg GDM kg^{-1} N) (Bigeriego et al., 1979; Huggins and Pan, 1993; Kamprath et al., 1982; Torbert et al., 2001; Wortmann et al., 2011). Average IE_E (across all site-years and application timings) was 53 kg GDM kg^{-1} N with approximately 79% of the observations between 46 and 60 kg GDM kg^{-1} N, which was similar to IE_E for recent hybrid studies (47 to 56 kg GDM kg^{-1} N) (Ciampitti and Vyn, 2012; Woli et al., 2016). The IE_E was not related to EONR or GDM_E across all site-years and N application timings. However, plant parameters at physiological maturity (GNC_E, SDM_E, SNC_E, and PMN_E) were negatively related with IE_E. In general, timing of N did not affect IE_E, however, when timing did affect IE_E 70% were higher with N spilt-applied possibly due to lower PMN_E, rather than increased GDM_E.

The third objective of this study was to evaluate weather, soil characteristics, soil NO_3-N, crop reflectance, and plant variables relationship with IE_E across all site-years. Most measures of weather (amount and distribution of rainfall and high temperature) and soil NO_3-N (determined at various times during the growing season) were not related to IE_E across all site-years and N application timings.

Plant available water content at various soil depths was generally negatively related with IE_E across all site-years perhaps in part due to the positive relationship between PAWC and the retention of residual N in the plant at VT and greater SDM at physiological maturity.

Crop reflectance collected at the V9 (±1 V-stage) leaf stage (sufficiency and simple ratio indices for both NDVI and NDRE at 0 and 45 kg N ha^{-1}) were negatively related to IE_E across all site-years, which was possibly a result of the positive relationship between sufficiency and simple ratio indices with plant N content at VT and PMN at the 0 and 45 kg N ha^{-1} treatments. However, plant variables (VTN, PMN, HI, and NHI of the 0 and 45 kg N ha^{-1}) were the strongest variables related with IE_E, especially plant N content at VT (VTN_0 and VTN_{45}). These variables were negatively (VTN and PMN of the 0 and 45 kg N ha^{-1}) or positively (HI and NHI of the 0 and 45 kg N ha^{-1}) related to IE_E perhaps in part due to their reflection of reduced or increased, respectively, retention of residual and available N and/or stover dry matter in the plant.

Based on the research conducted across these eight states over three years, it suggests environmental factors increasing or decreasing the retention of residual or available N in the plant and/or stover dry matter reflected IE_E.

Using models to predict IE_E, instead of a static value of IE_E, should improve yield-goal based models for predicting EONR. Post-sidedress model utilized weather, soil characteristics, soil NO_3-N, and crop reflectance to account for a maximum of 62% of the variation of IE_E. Majority of the variation in IE_E was accounted by PAWC0-30 (18%) which correlated with greater VTN and PMN. The remaining variation was accounted for by nine other variables though none exceed a partial R^2 of 0.07. The rescue application model (VT or later) used five variables to account for 54% of the variation in IE_E with a large amount of the variation accounted for by VTN_{45} (34%) likely due to its reflection of PMN. Models created prior to sidedress only accounted for 19 and 47% of the variation in IE_E using variables taken prior to N applied at-planting and sidedress (V9±1 leaf stage), respectively.

Moving forward these models will need to be validated to test their ability to predict IE_E. Additional research is also needed to find variables or combination of variables taken prior to at-planting or sidedress N that better predicts IE_E. Based on this research, these variables will reflect N loss or retention of residual N.

Table 1. Site description (slope, soil series, and soil family) for each productivity site (Prod.) (high (H) and low (L) based on historical yield data) across eigth states over three years (2014, 2015, and 2016).

State	Year	Site	Prod.	Slope	Soil Series	Family
				%		
IA	2014	MasonCity	H	1	Readlyn	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
		Ames	L	4	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls
	2015	Lewis	H	5	Marshall	Fine-silty, mixed, superactive, mesic Typic Hapludolls
		Boone	L	2	Clarion- Webster	Fine-loamy, mixed, superactive, mesic Typic Hapludolls Fine-loamy, mixed, superactive, mesic Typic Endoaquolls
	2016	Crawford	H	2	Mahaska	Fine, smectitic, mesic Aquertic Argiudolls
		Story	L	2	Canisteo	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls
IL	2014	Urbana	H	2	Flanagan	Fine, smectitic, mesic Aquic Argiudolls
		Brownstown	L	2	Cisne	Fine, smectitic, mesic Mollic Albaqualfs
	2015	Urbana	H	2	Flanagan	Fine, smectitic, mesic Aquic Argiudolls
		Brownstown	L	2	Cisne	Fine, smectitic, mesic Mollic Albaqualfs
	2016	Urbana	H	2	Flanagan	Fine, smectitic, mesic Aquic Argiudolls
		Shumway	L	2	Cisne	Fine, smectitic, mesic Mollic Albaqualfs

Table 1. Continued.

State	Year	Site	Prod.	Slope	Soil Series	Family
				%		
IN	2014	Loam	H	1	Sebewa	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiaquolls
		Sand	L	1	Tracy	Coarse-loamy, mixed, active, mesic Ultic Hapludalfs
	2015	Loam	H	1	Sebewa	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiaquolls
		Sand	L	1	Tracy	Coarse-loamy, mixed, active, mesic Ultic Hapludalfs
	2016	Loam	H	1	Sebewa	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiaquolls
		Sand	L	1	Tracy	Coarse-loamy, mixed, active, mesic Ultic Hapludalfs
MN	2014	NewRichland	H	2	Canisteo-Glencoe-Webster	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls Fine-loamy, mixed, superactive, mesic Typic Endoaquolls
		St. Charles	L	6	Seaton	Fine-silty, mixed, superactive, mesic Typic Hapludalfs
	2015	NewRichland	H	0-2	Webster-Nicollet	Fine-loamy, mixed, superactive, mesic Typic Endoaquolls Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
		St. Charles	L	2-6	Seaton	Fine-silty, mixed, superactive, mesic Typic Hapludalfs
	2016	Becker	H	3	Hubbard-Mosford	Sandy, mixed, frigid Entic Hapludolls Sandy, mixed, frigid Typic Hapludolls
		Waseca	L	2	Cordova	Fine-loamy, mixed, superactive, mesic Typic Argiaquolls

Table 1. Continued.

State	Year	Site	Prod.	Slope	Soil Series	Family
				%		
MO	2014	Troth	H	0	Lowmo	Coarse-silty, mixed, superactive, mesic Fluventic Hapludolls
		Bay	L	3	Mexico	Fine, smectitic, mesic Vertic Epiaqualfs
	2015	Troth	H	0-2	Lowmo	Coarse-silty, mixed, superactive, mesic Fluventic Hapludolls
		LoneTree	L	0-2	Mexico	Fine, smectitic, mesic Vertic Epiaqualfs
	2016	Loess	HA	9	Higginsville	Fine-silty, mixed, superactive, mesic Aquic Argiudolls
		Troth	HB	2	Peers	Fine-silty, mixed, superactive, mesic Fluvaquentic Hapludolls
		Bradford	L	2	Mexico	Fine, smectitic, mesic Vertic Epiaqualfs
ND	2014	Amenia	H	1	Glyndon- Tiffany	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls Coarse-loamy, mixed, superactive, frigid Typic Endoaquolls
		Durbin	L	1	Fargo	Fine, smectitic, frigid Typic Epiaquerts
	2015	Amenia	H	0-1	Lankin	Fine-loamy, mixed, superactive, frigid Pachic Hapludolls
		Durbin	L	0-1	Fargo	Fine, smectitic, frigid Typic Epiaquerts
	2016	Amenia	H	1	Glyndon	Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls
		Durbin	L	1	Hegne	Fine, smectitic, frigid Typic Calciaquerts

Table 1. Continued.

State	Year	Site	Prod.	Slope	Soil Series	Family
				%		
NE	2014	SCAL	H	1	Crete	Fine, smectitic, mesic pachic Udertic Argiustolls
		Brandes	L	3	Libory	Sandy over loamy, mixed, superactive, mesic Oxyaquic Haplustolls
	2015	SCAL	H	0-1	Crete	Fine, smectitic, mesic pachic Udertic Argiustolls
		Brandes	L	0-2	lpage	loamy fine sand
	2016	SCAL	H	1	Hastings	Fine, smectitic, mesic Udic Argiustolls
		Kyes	L	1	Lockton	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Cumulic Haplustolls
WI	2014	Steuben	H	1	Huntsville	Fine-silty, mixed, superactive, mesic Cumulic Hapludolls
		Wauzeka	L	15	Pepin	Fine-silty, mixed, superactive, mesic Typic Hapludalfs
	2015	Belmont	H	2-6	Tama	Fine-silty, mixed, superactive, mesic Typic Argiudolls
		Dalington	L	6-12	Dodgeville	Fine-silty over clayey, mixed, superactive, mesic Typic Argiudolls
	2016	Plano	H	2	Plano	Fine-silty, mixed, superactive, mesic Typic Argiudolls
		Lorenzo	L	12	Lorenzo	Fine-loamy over sandy or sandy-skeletal, mixed, active, mesic Typic Argiudolls

Table 2. Management description for each productivity site (Prod.) (high (H) and low (L) based on historical yield data) across eight states over three years (2014, 2015, and 2016).

State	Year	Prod.	Hybrid	Previous Crop	Tiled	Irrigated	Tillage†	Harvest Population	Seeding rate	Row Spacing
								plants ha^{-1}	seed ha^{-1}	cm
IA	2014	H	P0636	soy	yes	no	NT	79011	86484	76
		L	P0987	soy	no	no	C	86945	87719	76
	2015	H	P1498	soy	no	no	NT	79934	85248	76
		L	P0987	soy	no	no	C	84045	86484	76
	2016	H	P1197	soy	yes	no	C	84322	86484	76
		L	P1197	soy	yes	no	C	83694	86484	76
IL	2014	H	P1498	soy	no	no	C	81843	86484	76
		L	P1498	soy	no	no	C	85183	79071	76
	2015	H	P0987	soy	n/a	no	C	75674	86484	76
		L	P1498	soy	no	no	C	88200	86484	76
	2016	H	P1197	soy	n/a	no	C	82859	88955	76
		L	P1197	soy	no	no	SC/VT	66902	79071	76
IN	2014	H	P0987	soy	no	no	FCH/SC	70299	81542	76
		L	P0987	soy	no	no	FCH/SC	71530	81542	76
	2015	H	P0987	soy	no	no	FDR/SC	81128	80306	76
		L	P0987	soy	no	no	FDR/SC	80418	80306	76
	2016	H	P1197	soy	no	no	FDR/SC	80177	80306	76
		L	P1197	soy	no	no	FCH/SC	80365	80306	76
MN	2014	H	P9917	soy	yes	no	C	84721	85248	76
		L	P9917	soy	no	no	VT	82610	85248	76
	2015	H	P0157	soy	yes	no	C	80811	87719	76
		L	P0157	soy	no	no	VT	86461	85248	76
	2016	H	P0157	soy	no	yes	SD/C	74336	87719	76
		L	P0157	soy	no	no	FD/SC	85284	87719	76

Table 2. Continued

State	Year	Prod.	Hybrid	Previous Crop	Tiled	Irrigated	Tillage†	Harvest Population	Seeding rate	Row Spacing
								plants ha^{-1}	seed ha^{-1}	cm
MO	2014	H	P1498	soy	no	no	NT	82442	86484	76
		L	P1498	soy	no	no	C	83947	86484	76
	2015	H	P1498	soy	no	no	C	87031	86484	76
		L	P1498	soy	no	no	C	83298	86484	76
	2016	HA	P1197	soy	no	no	C	78061	84013	76
		HB	P1197	soy	no	yes	SD/C	77565	86484	76
		L	P1197	soy	no	no	SD/C	74268	86484	76
ND	2014	H	P8954	corn	no	no	FCH/SC	67027	79071	56
		L	P8954	corn	yes	no	FCH/SC	71125	79071	56
	2015	H	P9188	corn	no	no	FCH/SC	79870	84013	56
		L	P9188	corn	yes	no	FCH/SC	75375	84013	56
	2016	H	P9188	soy	no	no	FCH/SC	86033	93897	56
		L	P9188	sunflower	yes	no	FCH/SC	85620	88955	56
NE	2014	H	P1151	soy	no	yes	NT	79785	79071	76
		L	P1151	soy	no	yes	NT	87437	86484	76
	2015	H	P1151	soy	no	yes	NT	81433	84013	76
		L	P1151	soy	no	yes	NT	81786	86484	76
	2016	H	P1197	corn	no	yes	NT	79415	84013	76
		L	P1197	soy	no	yes	NT	73730	79071	76
WI	2014	H	P0636	soy	no	no	NT	83700	86484	76
		L	P0636	soy	no	no	NT	84210	79812	89
	2015	H	P0987	soy	no	no	NT	79865	93155	76
		L	P0987	soy	no	no	NT	80747	90190	76
	2016	H	P0157	soy	no	no	NT	84830	86484	76
		L	P0157	soy	no	no	NT	85981	86484	76

Table 3. Dates for planting, pre-plant soil NO3-N test (PPNT), N applied at-planting, pre-sidedress soil NO3-N test (PSNT: V5±1 V-stage), crop reflectance canopy sensing, split-applied N (V9±1 V-stage), whole plant biomass sampling at tasseling (VT), plant stage of biomass sampling, soil NO3-N at tasseling (VTNT), whole plant biomass sampling at physiological maturity (R6), harvest date, and post-harvest soil NO3-N test (PHNT) for each productivity sites (Prod.) (high (H) and low (L) based on historical yield data) across eight states over three years (2014, 2015, and 2016).

State	Year	Prod.	Planting	PPNT	At-Planting N App	PSNT	Canopy Sensing	Spilt-Applied N	Biomass Sampling (VT)	Plant Sampling Stage	VTNT	Biomass Sampling (R6)	Harvest	PHNT
IA	2014	H	9-May	9-May	15-May	10-Jun	9-Jul	3-Jul	23-Jul	VT	n/a	7-Oct	16-Oct	8-Nov
		L	7-May	22-Apr	9-May	9-Jun	26-Jun	26-Jun	15-Jul	VT	n/a	10-Oct	17-Oct	28-Oct
	2015	H	29-Apr	31-Mar	1-May	19-Jun	7-Jul	9-Jul	21-Jul	VT	21-Jul	22-Sep	4-Oct	22-Oct
		L	18-May	30-Mar	19-May	19-Jun	7-Jul	9-Jul	31-Jul	VT	31-Jul	25-Sep	8-Oct	12-Oct
	2016	H	26-Apr	5-Apr	5-May	6-Jun	20-Jun	20-Jun	25-Jul	VT	25-Jul	14-Sep	30-Oct	3-Nov
		L	12-May	22-Mar	16-May	15-Jun	28-Jun	5-Jul	26-Jul	VT	26-Jul	1-Oct	19-Oct	20-Oct
IL	2014	H	25-Apr	23-Apr	26-Apr	28-May	15-Jun	16-Jun	7-Jul	VT	7-Jul	11-Sep	29-Sep	7-Oct
		L	24-Apr	24-Apr	25-Apr	30-May	13-Jun	13-Jun	2-Jul	V17-V18	2-Jul	8-Sep	1-Oct	8-Oct
	2015	H	23-Apr	7-Apr	24-Apr	28-May	15-Jun	15-Jun	9-Jul	VT-R1	9-Jul	10-Sep	24-Sep	29-Sep
		L	28-Apr	22-Apr	29-Apr	3-Jun	16-Jun	16-Jun	12-Jul	R1	12-Jul	11-Sep	23-Sep	28-Sep
	2016	H	19-Apr	30-Mar	19-Apr	31-May	13-Jun	13-Jun	8-Jul	VT-R1	8-Jul	13-Sep	27-Sep	4-Oct
		L	25-Apr	29-Mar	27-Apr	2-Jun	16-Jun	16-Jun	11-Jul	VT-R1	11-Jul	12-Sep	21-Sep	3-Oct
IN	2014	H	19-May	21-May	23-May	16-Jun	27-Jun	30-Jun	23-Jul	R1	n/a	27-Sep	21-Oct	29-Oct
		L	19-May	21-May	22-May	16-Jun	27-Jun	30-Jun	23-Jul	R1	n/a	27-Sep	22-Oct	28-Oct
	2015	H	29-Apr	30-Apr	1-May	3-Jun	17-Jun	24-Jun	20-Jul	VT	15-Jul	25-Sep	22-Oct	26-Oct
		L	29-Apr	30-Apr	1-May	3-Jun	17-Jun	24-Jun	22-Jul	VT	16-Jul	25-Sep	22-Oct	26-Oct
	2016	H	20-May	25-Apr	20-May	9-Jun	28-Jun	29-Jun	27-Jul	VT	27-Jul	3-Oct	12-Oct	20-Oct
		L	20-May	25-Apr	20-May	9-Jun	28-Jun	29-Jun	27-Jul	VT	27-Jul	3-Oct	16-Oct	20-Oct
MN	2014	H	21-May	6-May	23-May	10-Jun	7-Jul	7-Jul	29-Jul	R1	.	19-Sep	22-Oct	29-Oct
		L	16-May	6-May	20-May	6-Jun	8-Jul	8-Jul	28-Jul	R1	.	23-Sep	28-Oct	30-Oct
	2015	H	18-Apr	15-Apr	23-Apr	10-Jun	26-Jun	26-Jun	20-Jul	VT-R1	20-Jul	30-Sep	8-Oct	12-Oct
		L	1-May	15-Apr	8-May	16-Jun	1-Jul	1-Jul	22-Jul	V15	22-Jul	24-Sep	20-Oct	27-Oct
	2016	H	27-Apr	21-Apr	2-May	6-Jun	22-Jun	22-Jun	19-Jul	VT	19-Jul	20-Sep	14-Oct	19-Oct
		L	6-May	22-Apr	16-May	21-Jun	27-Jun	27-Jun	22-Jul	R1	22-Jul	16-Sep	24-Oct	2-Nov

Table 3. Continued.

State	Year	Prod.	Planting	PPNT	At-Planting N App	PSNT	Canopy Sensing	Spilt-Applied N	Biomass Sampling (VT)	Plant Sampling Stage	VTNT	Biomass Sampling (R6)	Harvest	PHNT
MO	2014	H	2-May	26-Mar	6-May	30-May	21-Jun	16-Jun	2-Jul	VT	2-Jul	26-Aug	14-Sep	19-Sep
		L	2-May	26-Mar	7-May	3-Jun	20-Jun	18-Jun	7-Jul	VT	7-Jul	27-Aug	14-Sep	22-Sep
	2015	H	14-Apr	6-Apr	15-Apr	21-May	10-Jun	10-Jun	30-Jun	VT	30-Jun	21-Aug	10-Sep	23-Sep
		L	17-Apr	16-Apr	17-Apr	23-May	19-Jun	19-Jun	10-Jul	VT	10-Jul	28-Aug	17-Sep	25-Sep
	2016	HA	6-Apr	4-Apr	8-Apr	20-May	6-Jun	6-Jun	29-Jun	R1	29-Jun	25-Aug	27-Sep	6-Oct
		HB	13-Apr	1-Apr	16-Apr	19-May	3-Jun	3-Jun	28-Jun	R1	28-Jun	22-Aug	27-Sep	29-Sep
		L	16-Apr	20-Apr	20-Apr	30-May	13-Jun	13-Jun	5-Jul	VT	5-Jul	1-Sep	3-Oct	11-Oct
ND	2014	H	23-May	24-Apr	30-May	8-Jul	10-Jul	26-Jun	29-Jul	VT	.	30-Sep	1-Oct	14-Oct
		L	23-May	1-May	30-May	26-Jun	10-Jul	8-Jul	29-Jul	VT	.	1-Oct	15-Oct	15-Oct
	2015	H	24-Apr	22-Apr	23-Apr	14-Jun	14-Jun	18-Jun	23-Jul	VT	.	11-Sep	17-Sep	22-Sep
		L	24-Apr	23-Apr	23-Apr	18-Jun	18-Jun	18-Jun	27-Jul	VT	.	9-Sep	16-Sep	22-Sep
	2016	H	6-May	12-Apr	4-May	17-Jun	17-Jun	17-Jun	25-Jul	VT	25-Jul	12-Sep	7-Oct	18-Oct
		L	6-May	5-May	6-May	16-Jun	21-Jun	17-Jun	26-Jul	VT	26-Jul	12-Sep	16-Oct	18-Oct
NE	2014	H	7-May	16-Apr	2-May	6-Jun	24-Jun	25-Jun	7-Jul	VT	9-Jul	22-Sep	22-Oct	4-Nov
		L	19-Apr	16-Apr	22-Apr	10-Jun	26-Jun	26-Jun	15-Jul	VT	15-Jul	24-Sep	3-Oct	4-Nov
	2015	H	24-Apr	23-Mar	13-Apr	2-Jun	24-Jun	24-Jun	28-Jul	R2	22-Jul	16-Sep	8-Oct	14-Oct
		L	19-Apr	24-Mar	10-Apr	2-Jun	29-Jun	30-Jun	30-Jul	R2	14-Jul	16-Sep	12-Oct	13-Oct
	2016	H	12-May	.	13-Apr	13-Jun	28-Jun	29-Jun	18-Jul	VT	18-Jul	7-Oct	18-Oct	27-Oct
		L	5-May	.	12-Apr	8-Jun	21-Jun	22-Jun	.	.	.	29-Sep	29-Sep	26-Oct
WI	2014	H	7-May	7-May	7-May	10-Jun	25-Jun	25-Jun	24-Jul	VT	24-Jul	29-Sep	5-Nov	7-Nov
		L	6-May	7-May	7-May	10-Jun	25-Jun	25-Jun	24-Jul	VT	24-Jul	29-Sep	5-Nov	7-Nov
	2015	H	4-May	6-May	6-May	16-Jun	1-Jul	1-Jul	29-Jul	VT	29-Jul	5-Oct	21-Oct	26-Oct
		L	4-May	6-May	6-May	16-Jun	1-Jul	1-Jul	29-Jul	VT	29-Jul	5-Oct	21-Oct	26-Oct
	2016	H	23-Apr	29-Apr	29-Apr	13-Jun	30-Jun	30-Jun	26-Jul	VT	26-Jul	26-Sep	24-Oct	1-Nov
		L	23-Apr	29-Apr	29-Apr	10-Jun	27-Jun	27-Jun	26-Jul	VT	26-Jul	26-Sep	24-Oct	1-Nov

Table 4. Additional fertilizer, fertilizer rate, timing, and pesticide application and date at each productivity site (Prod.) (high (H) and low (L) based on historical yield data) across eight state over three years (2014, 2015, and 2016).

State	Year	Prod.	Fertilizer	Rate	Timing	Pesticide	Date
				kg ha^{-1}			
IA	2014	H	0-0-0-21S	19	V4	Roundup PowerMax(Glyphosate) (Monsanto Company, St. Louis, MO) 1.2 L ha^{-1}; 2,4D, 1.2 L ha^{-1}, (2,4-Dichlorophenoxyacetic acid); Corvus, 400 ml ha^{-1}; Impact, 600 ml ha^{-1}, (Topramezone [3-(4,5-dihydro-3-isoxazolyl)-2-methyl-4-(methylsulfonyl) phenyl] (5-hydroxy-1-methyl-1H-pyrazol-4-yl) methanone) (AMVAC, Inc., Los Angeles, CA); Abundit Extra, 2.3 L ha^{-1}, (Glyphosate, N-(phosphonomethyl) glycine, isopropylamine salt) (Nufarm Inc., Burr Ridge, IL)	5/7, 5/7, 5/7, 5/23, 6/17, 6/17
		L	.	.	.	SureStart 2.3 L ha^{-1}, (acetochlor: 2-chloro-2'-methyl-6'-ethyl-N-ethoxymethylacetanilide) (Dow Agrosciences, Inc., Indianapolis, IN)	5/7
	2015	H	0-46-0, 0-0-60	134, 190	.	Roundup (Glyphosate) + Intense, 710 ml + 946 ml 3.8 L^{-1}; Roundup (Glyphosate) 710 ml + Outlook 591 ml (dimethenamid-P: (S)-2-chloro-N-[(1-methyl-2-methoxy) ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamide) + Atrazine 454 g + 2,4 D 473 ml (2,4-Dichlorophenoxyacetic acid)+ Intense 2.5 ml L^{-1}	6/8, 5/4
		L	0-46-0	179	.	Bicep II Mangnum (Atrazine) (Syngenta Crop Protection, Inc., Greensboro, NC) (4.9 L ha^{-1}	5/13
	2016	H	0-0-60, 0-0-0-21S	168, 101	Fall	Zidua 3-[[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)-1H-pyrazol-4yl]-4,5-dihydro-5,5-dimethylisoxazole) (BASF Corporation, Research Triangle Park, NC) 0.14 kg ha^{-1}; Atrazine 1.7 kg ha^{-1}; Halex GT (S-metolachlor)/(Glyphosate, N-(phosphonmethyl) glycine) (Syngenta Crop Protection, Inc., Greensboro, NC) 4 680 ml ha^{-1}; Atrazine 0.56 kg ha^{-1}	5/5, 5/5, 5/5, 6/2
		L	0-46-0, 0-0-60, 0-0-0-91S	247, 168, 22	Fall	Impact 0.05 kg ha^{-1}	6/18

Table 4. Continued.

State	Year	Prod.	Fertilizer	Rate	Timing	Pesticide	Date
				kg ha^{-1}			
IL	2014	H	.	.	.	Lumax (S-metolachlor)/(atrazine) (Syngenta Crop Protection, Inc., Greensboro, NC) 4.7 L ha^{-1}	5/27
		L	.	.	.	Marksman (atrazine 2-chloro-ethylamino-6-isopropyl/amino-s-triazine) (BASF, Corp., Research Triangle Park, NC), 4.1 L ha^{-1}; Frontier (Dimethenamid: 2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimthyl-thien-3-yl)-acetamide) (BASF, Corp., Research Triangle Park, NC), 1.2 L ha^{-1}; Roundup WeatherMax, 1.6 L ha^{-1}	5/21, 5/21, 5/21
	2015	H	.	.	.	Halex GT, 4.7 L ha^{-1}	6/5
		L	.	.	.	Aatrex Nine-O (Atrazine: 2-chloro-4-ethylamino-6-isopropylamino-s-triazine) (Syngenta Crop Protection, Inc., Greensboro, NC) 2.2 kg ha^{-1}; Banvel (Dimethylamine salt of dicamba (3, 6-dichloro-o-anisic acid) (Arysta LifeScience North America, LLC., Cary, NC) 1.2 L ha^{-1}; Frontier, 1.3 L ha^{-1}; Roundup, 1.6 L ha^{-1}	5/15
	2016	H	.	.	.	Harness (Acetochlor) (Monsanto Company, St. Louis, MO) 5.8 L ha^{-1}; Halex GT, 4.7 L ha^{-1}	4/18, 6/8
		L	.	.	.	Abundit Extra 3.0 L ha^{-1}; Atrazine 1.7 kg ha^{-1}; Realm Q (N-((4,6-dimethoxpyrimidin-2-yl) aminocarbony)-3-(ethylsulfony)-2-pyridinesulfonamide) (Mesotrione) (DuPont, de Nemours and Company, Wilmington, DE) 320 ml ha^{-1}	5/24

Table 4. Continued.

State	Year	Prod.	Fertilizer	Rate	Timing	Pesticide	Date
				kg ha^{-1}			
IN	2014	H	0-0-60	308	Fall	Bicep II Magnum, 4.9 L ha^{-1}; Balance Flexx Isoxaflutole [5-cycloprpyl-4-(2-methylsulfonyl-4- trifluoramethylbenzoyl) isoxazole], 219 ml ha^{-1}; Callisto®xtra, 1.5 L ha^{-1}	4/30, 4/30, 6/3
		L	11-52-0, 0-0-60	213, 308	Fall	Bicep II Magnum, 219 ml ha^{-1}; Callisto®xtra (atrazine) (Syngenta Crop Protection, Inc., Greensboro, NC), 1.5 L ha^{-1}	4/30, 4/30, 6/3
	2015	H	0-46-0, 0-0-0-5Mn	207, 0.28	2/1, 6/3	Bicep II Magnum, 4.9 L ha^{-1}; Callisto®xtra, 1.5 L ha^{-1}	5/1, 5/28
		L	0-0-60, 0-46-0, 0-0-0-21S	336, 207, 140	2/1	Bicep II Magnum, 4.9 L ha^{-1}; Callisto®xtra, 1.5 L ha^{-1}	5/1, 5/18
	2016	H	0-46-0, 0-0-60	381, 95	Fall	Fultime NXT 7 L ha^{-1}; Callisto®xtra 1.4 kg ha^{-1}	4/29, 6/8
		L	0-0-0-21S	140	Fall	Fulltime NXT (acetochlor: 2-chloro-N-ethoxymethyl-N-(2-ethyl6-4-methylphenyl) acetamide) (Dow Agrosciences, Inc., Indianapolis, IN) 7 L ha^{-1}; Callisto®xtra 1.4 kg ha^{-1}	4/20, 5/25

Table 4. Continued.

State	Year	Prod.	Fertilizer	Rate	Timing	Pesticide	Date
				kg ha^{-1}			
MN	2014	H	0-46-0, 0-0-60, 0-0-0-21S	90, 90, 22	.		
		L	0-0-0-21	19	.	Touchdown (Glyphosate: N-(phosphonomethyl) glycine) (Syngenta Crop Protection, Inc., Greensboro, NC) 2 L ha^{-1}, post emergent; Status (Sodium salt of diflufenzopyr: 2-(1-[([3,5-difuorophenylamino] carbonyl)-hydrazono]ethyly)-3-pyridinecarboxylic acid) and (Sodium salt of dicamba: 3,6-dichloro-2-methoxybenzoic acid) (BASF, Corp., Research Triangle Park, NC), 256 ml ha^{-1}, post emergent; Class act (Ammonium sulfate, high fructose corn syrup, substituted fatty alkylammonium alkylcarboxylate, alkyl poly glucoside) (Winfield Solutions LLC., St. Paul, MN) 1.8 L ha^{-1}, post emergent	post-emergent
	2015	H	0-46-0, 0-0-60, 0-0-0-21S	124, 112, 66	.	Breakfree (acetochlor: 2-chloro-2'-methyl-6'-ethyl-N-ethoxymethylacetanilide) (DuPont Crop Protection Inc., Wilmington, DE) 103 L ha^{-1}; Abundit Extra 75 L ha^{-1}; Realm Q 8.2 L ha^{-1}	4/29, 6/14
		L	46-0-0, 0-0-48-17S	67, 134	.	Lumax, 6.3 L ha^{-1}; Cornerstone®5 (Glyphosate, N-(phosphonomethly) glycine) (Winfield Solutions LLC., St. Paul, MN), 2.3 L ha^{-1}	6/2
	2016	H	0-0-22-22mg, 0-0-60, 0-46-0	224, 224, 146	.	Lumax 5.3 L ha^{-1}; Makaze (Glyphosate, N-(phosphonomethyl) glycine) (LoveLand Inc., Greeley, CO) 1.47 kg ha^{-1}; spot sprayed Makaze 2.2 kg ha^{-1}	4/28, 5/11, 7/13
		L	0-0-40-17S, 0-46-0	112, 146	.	Triple Flex 3.5 L ha^{-1}; Realm Q 0.28 kg ha^{-1}, Abundit Extra 2.2 kg ha^{-1}, Atrazine 0.5 kg ha^{-1}	5/10, 3/2

Table 4. Continued.

State	Year	Prod.	Fertilizer	Rate	Timing	Pesticide	Date
				kg ha^{-1}			
MO	2014	H	0-0-0-21S	21	6/19		
		L		.	.		
	2015	H	0-0-0-18.6S	179	4/14	Halex GT, 4.7 L ha^{-1}; Atrazine 1.1 L ha^{-1}; Actuvatir 90 AMS 1.1 L ha^{-1}	5/18
		L	0-45-0, 0-0-60	101, 146	4/16	Halex GT, 4.7 L ha^{-1}; Atrazine 1.1 L ha^{-1}; Activator 90 AMS (alkylphenol ethoxylate, alcohol ethoxylate and tall oil fatty acid) 1.1 L ha^{-1}	5/18
	2016	HA	.	.	.	Degree Xtra (acetochlor, 2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide) (Monsanto Company, St. Louis, MO) 3.5 L ha^{-1}, Atrazine 1.1 kg ha^{-1}; Roundup 2.3 L ha^{-1}, Atrazine 4L 1.1 kg ha^{-1}	
		HB	.	.	.	Corvus 0.3 L ha^{-1}, Atrazine 4.7 L ha^{-1}; Liberty 2.1 L ha^{-1}	4/15, 5/30
		L	.	.	.	Ignite (Glufosinate-ammonium) (Bayer CropScience LP, Research Triangle Park, NC) 2.1 L ha^{-1}, Atrazine 4L 3.6 L ha^{-1}, and Parallel 1.8 L ha^{-1}; Buckenere 3.2 L ha^{-1}, Atrazine 4L 2.4 L ha^{-1}	4/29, 5/24

Table 4. Continued.

State	Year	Prod.	Fertilizer	Rate	Timing	Pesticide	Date
				kg ha^{-1}			
ND	2014	H	.	.	.	Harness, 2.8 L ha^{-1}; Roundup PowerMax, 1.6 L ha^{-1}; Roundup PowerMax, 1.6 L ha^{-1}	5/30, 6/25, 7/10
		L	0-0-0-21S	112	6/26	Harness 2.3 L ha^{-1}; Roundup PowerMax, 1.6 L ha^{-1}; Roundup PowerMax, 1.6 L ha^{-1}	5/30, 6/10, 6/25
	2015	H	0-0-0-21S	112	4/22	Harness 2.6 L ha^{-1}; Roundup PowerMax 1.6 L ha^{-1}	4/27, 5/22
		L	0-0-0-21S, 0-46-0	112, 168	4/23	Harness 3.2 L ha^{-1}; Roundup PowerMax 1.6 L ha^{-1}	4/27, 5/22
	2016	H	46-0-0, 21-0-0-24S, 0-0-0-20S	85, 28, 112	6/14	Harness 3.2 L ha^{-1}, Roundup PowerMax 1.5 kg ha^{-1}, Roundup PowerMax 1.5 kg ha^{-1}	5/9, 5/9, 6/2
		L	.	.	.	Harness 3.2 L ha^{-1}, Roundup PowerMax 1.5 kg ha^{-1}, Roundup PowerMax 1.5 kg ha^{-1}	5/20, 5/20, 6/2

Table 4. Continued.

State	Year	Prod.	Fertilizer	Rate	Timing	Pesticide	Date
				kg ha^{-1}			
NE	2014	H	11-52-0, 10-34-0	112, 65	Fall, 5/7	Lexar (S-metolachlor)/(Atrazine) (Syngenta Crop Protection, Inc., Greensboro, NC), 1.1 L ha^{-1}; Roundup PowerMax, 2.3 L ha^{-1}	5/9
		L	11-52-0	112	.	.	.
	2015	H	11-52-0, 10-34-0	112, 65	Fall, 4/24	Lexar, 7.0 L ha^{-1}; Roundup PowerMax 2.9 L ha^{-1}	4/29
		L	11-52-0	112	3/1	Roundup PowerMax + Bicept II Magnum®	4/19
	2016	H	11-52-0, 10-34-0	112, 65	5/12	Roundup 2.3 L ha^{-1}, 2,4-D broadcast 580 ml ha^{-1}; Acuron 5.9 L ha^{-1}, Roundup broadcast 1.1 kg ha^{-1}	4/8, 5/14
		L	10-34-0	65	5/5	Unknown herbicide and rate	5/7
WI	2014	H	0-46-0, 0-0-40-17	112, 202	5/2	Harness, 2.6 L ha^{-1}; Hornet (Flumetsulam: N-(2,6-difluoropheny)-5-methyl-1,2.4-triazolo-[1,5a]-primidine-2-sulfonamide), (clopyralid potassium salt: 3,6-dichloro-2-pyridinecarboxylic acid, potassium salt) (Dow AgroScience LLC., Indianapolis, IN), 292 ml ha^{-1}; Sterling Blue (Diglycolamine salt of 3,6-dichloro-o-anisic acid) (Winfield Solutions, LLC., St. Paul, MN) 600 ml ha^{-1}	5/8
		L	.	.	.	SuresStart, 3.5 L ha^{-1}; Volley ATZ Lite (Acetochlor: 2-chloro-2'-methyl-6'-ethyl-N-ethoxymethylacetanilide)(atrazine: [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine]) (Dow AgroScience LLC., Indianapolis, IN), 1.8 L ha^{-1}; Roundup PowerMax, 1.8 L ha^{-1}; AMS (ammonium salts, polyacrylamide polymer, and siloxane) (United Suppliers, Inc., Eldora, IA), 1.6 kg ha^{-1}	pre-emergent
	2015	H	.	.	.	Glyphosate 0.8 kg ha^{-1}; Glyphosate 0.8 kg ha^{-1}	5/21, 6/25
		L	.	.	.	Glyphosate 0.8 kg ha^{-1}; Glyphosate 0.8 kg ha^{-1}	5/21, 6/25
	2016	H	.	.	.	Pre-emergence herbicide mix, unknown rate	4/25
		L	.	.	.	Pre-emergence herbicide mix, unknown rate	4/25

Table 5. Routine soil samples taken at 0-15 cm for each productivity site (Prod.) (high (H) and low (L) based on historical yield data) across eight state over three years (2014, 2015, and 2016). Soil fertility results for pH, organic matter (OM), phosphorus (P), and potassium (K) along with extraction methods for P and K.

State	Year	Prod.	pH	OM†	P	K	P Method‡	K Method§
				%	--- kg ha^{-1} ---			
IA	2014	H	5.8	4.4	26	367	Bray 1	Mehlich III
		L	6.0	3.0	103	460	Bray 1	Mehlich III
	2015	H	6.2	3.6	66	336	Mehlich III	Mehlich III
		L	5.9	3.4	34	424	Mehlich III	Mehlich III
	2016	H	7.1	4.5	139	356	Mehlich III	Mehlich III
		L	6.2	4.2	22	318	Mehlich III	Mehlich III
IL	2014	H	5.4	3.3	85	365	Mehlich III	Mehlich III
		L	5.0	1.9	85	300	Mehlich III	Mehlich III
	2015	H	5.8	3.0	74	327	Mehlich III	Mehlich III
		L	6.3	1.7	65	419	Mehlich III	Mehlich III
	2016	H	5.4	3.8	58	260	Mehlich III	Mehlich III
		L	6.5	2.5	273	285	Mehlich III	Mehlich III
IN	2014	H	6.2	2.6	152	334	Mehlich III¶	Mehlich III¶
		L	6.7	1.5	96	316	Mehlich III	Mehlich III
	2015	H	6.3	3.1	126	345	Mehlich III	Mehlich III
		L	6.3	1.8	76	233	Mehlich III	Mehlich III
	2016	H	6.4	4.7	37	307	Mehlich III	Mehlich III
		L	6.8	1.8	253	307	Mehlich III	Mehlich III
MN	2014	H	7.8	6.9	4	446	Bray 1	Ammonium acetate
		L	6.8	3.1	25	260	Bray 1	Ammonium acetate
	2015	H	6.5	5.2	69	531	Bray 1	Ammonium acetate
		L	6.5	2.1	72	298	Bray 1	Ammonium acetate
	2016	H	6.0	1.8	38	448	Olsen P	Ammonium acetate
		L	5.8	5.7	38	522	Olsen P	Ammonium acetate

Table 5. Continued.

State	Year	Prod.	pH	OM†	P	K	P Method‡	K Method§
				%	--- kg ha^{-1} ---			
MO	2014	H	7.1	1.4	44	269	Bray 1	Ammonium acetate
		L	6.5	2.1	30	213	Bray 1	Ammonium acetate
	2015	H	7.3	1.6	64	446	Bray 1	Ammonium acetate
		L	6.4	2.3	37	185	Bray 1	Ammonium acetate
	2016	HA	6.0	2.4	119	492	Bray 1	Ammonium acetate
		HB	7.2	2.0	81	508	Bray 1	Ammonium acetate
		L	6.4	1.9	76	269	Bray 1	Ammonium acetate
ND	2014	H	7.6	4.2	18	471	Olsen P	Ammonium acetate
		L	7.6	5.9	74	1950	Olsen P	Ammonium acetate
	2015	H	7.6	4.1	49	502	Olsen P	Ammonium acetate
		L	7.8	6.8	16	706	Olsen P	Ammonium acetate
	2016	H	7.4	4.1	34	356	Olsen P	Ammonium acetate
		L	7.4	5.6	63	959	Olsen P	Ammonium acetate
NE	2014	H	6.9	3.3	45	758	Mehlich III	Ammonium acetate
		L	n/a	n/a	n/a	n/a	n/a	n/a
	2015	H	6.6	3.6	74	1027	Mehlich III	Ammonium acetate
		L	7.2	1.1	27	233	Mehlich III	Ammonium acetate
	2016	H	7.1	3.3	56	829	Mehlich III	Ammonium acetate
		L	6.8	2.4	43	684	Mehlich III	Ammonium acetate
WI	2014	H	6.7	3.9	26	276	Olsen P	Ammonium acetate
		L	5.8	4.0	77	341	Olsen P	Ammonium acetate
	2015	H	7.3	3.4	48	228	Bray 1	Bray 1
		L	6.6	4.5	36	452	Bray 1	Bray 1
	2016	H	6.5	3.7	218	659	Bray 1	Bray 1
		L	6.6	4.9	44	331	Bray 1	Bray 1

† IA = Dry Combustion; IL, IN, MN, MO, ND, NE, WI = Loss on Ignition.
‡ Mehlich III (Mehlich, 1978); Bray 1 (Bray and Kurtz, 1945); Olsen P (Olsen et at., 1954)
§ Ammonium acetate (Knudsen et al., 1982)
¶ Extracted method used in IN was Mechlich III then converted to Bray 1 (P) and ammonium acetate (K).
n/a = Data was not collected in 2014 for NE.

Table 6. The soil NO3-N test at pre-plant was obtained before planting from each replication, pre-sidedress (PSNT) (V5±1 V-stage), tasseling (VTNT), and post-harvest (PHNT) (one to four weeks after harvest) taken at different N treatments (Trt.) and timings (at-planting and split-applied N) for each productivity site (high and low based on historical yield data) across eight state over three years (2014, 2015, and 2016). Soil NO3-N sampling times represented by an 'X' are the treatments sampled at each site.

Trt.	Pre-Plant	Split	Total N	PSNT	VTNT	PHNT
	-------------- kg ha^{-1}	-------------		6 cores $plot^{-1}$	6 cores $plot^{-1}$	3 core $plot^{-1}$
1	0	0	0	X	X	X
2	45	0	45	X		X
3	90	0	90	X	X	X
4	135	0	135	X		X
5	180	0	180	X	X	X
6	225	0	225	X		X
7	270	0	270	X	X	X
8	315	0	315	X		X
9	45	45	90		X	X
10	45	90	134			X
11	45	135	180		X	X
12	45	180	225			X
13	45	225	270		X	X
14	45	270	315			X
15	90	90	179		X	X
16	90	180	270			X

Table 7. Total rainfall (TR) measured at different times during the growing season for eight states over a three year period (2014, 2015, and 2016) and two productivity sites (Prod. – high (H) and low (L) based on historical yield data) during ten days before N applied at at-planting (10dBPN), ten days after N applied at at-planting (10dAPN), ten days before and after N applied at-planting (10dBAPN), ten days before N split-applied (10dBSN), ten days after N split-applied (10dASN), ten days before and after N split-applied (10dBASN), vegetative (Vege.), two weeks before VT (2wkBVT), two weeks after VT (2wkAVT), two weeks before and after VT (2wkBAVT), during grain fill, and the whole growing season.

			Periods during the growing season											
Year	State	Prod.	10d-BPN	10d-APN	10d-BAPN	10d-BSN	10d-ASN	10d-BASN	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season
			TR (mm)											
2014	IA	H	49	8	57	88	9	97	339	7	16	23	133	471
2014	IA	L	36	47	80	94	90	174	357	41	5	46	382	739
2014	IL	H	8	50	50	51	75	126	414	123	109	232	260	674
2014	IL	L	27	79	81	71	3	74	242	16	57	72	307	549
2014	IN	H	46	27	73	153	46	179	337	38	41	64	160	497
2014	IN	L	64	20	84	168	45	195	358	34	37	55	146	504
2014	MN	H	12	50	63	22	13	35	301	10	9	20	156	457
2014	MN	L	49	9	52	21	8	29	258	12	9	21	41	298
2014	MO	H	29	41	70	55	12	64	169	23	29	53	76	245
2014	MO	L	32	59	91	38	50	88	239	35	41	61	97	336
2014	ND	H	7	20	27	38	28	58	154	16	5	22	109	264
2014	ND	L	13	25	38	11	9	19	174	13	0	13	107	282
2014	NE	H	46	75	121	70	37	106	287	59	45	83	253	540
2014	NE	L	17	57	74	28	21	48	310	12	1	13	187	497
2014	WI	H	38	42	80	115	71	186	319	11	28	39	176	495
2014	WI	L	43	67	110	131	119	250	399	4	12	16	107	506

Table 7. Continued.

Year	State	Prod.	10d-BPN	10d-APN	10d-BAPN	10d-BSN	10d-ASN	10d-BASN	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season
			Periods during the growing season											
			---------- TR (mm) ----------											
2015	IA	H	10	23	32	29	66	94	321	75	19	93	196	517
2015	IA	L	42	34	76	23	40	63	334	84	70	155	300	634
2015	IL	H	18	4	22	66	82	147	308	121	27	129	136	443
2015	IL	L	20	13	32	106	105	209	366	57	21	78	197	563
2015	IN	H	20	28	48	6	4	9	229	123	3	126	90	319
2015	IN	L	20	27	48	6	4	9	229	102	3	105	97	326
2015	MN	H	21	13	34	114	40	154	378	50	108	158	322	700
2015	MN	L	39	26	48	37	13	50	296	64	49	113	201	497
2015	MO	H	19	23	42	12	98	109	293	97	94	191	157	450
2015	MO	L	22	38	60	107	30	136	491	152	72	224	200	691
2015	ND	H	12	9	21	45	62	107	371	76	30	106	53	424
2015	ND	L	7	2	9	45	38	84	216	42	22	58	54	270
2015	NE	H	8	31	39	28	5	33	459	33	35	68	68	527
2015	NE	L	31	15	46	1	17	18	252	28	96	124	194	446
2015	WI	H	14	22	34	16	2	18	264	18	3	18	228	492
2015	WI	L	20	27	44	41	10	51	238	30	10	30	74	312

Table 7. Continued.

Year	State	Prod.	10d-BPN	10d-APN	10d-BAPN	10d-BSN	10d-ASN	10d-BASN	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season
			Periods during the growing season											
			TR (mm)											
2016	IA	H	52	27	79	5	38	43	321	132	11	143	169	489
2016	IA	L	21	37	58	7	57	64	226	76	12	88	399	622
2016	IL	H	16	38	53	33	103	135	334	66	55	121	329	663
2016	IL	L	74	86	125	10	1	10	329	117	63	181	323	652
2016	IN	H	35	2	36	16	4	20	137	103	19	122	376	512
2016	IN	L	32	1	33	13	4	18	128	95	19	114	404	532
2016	MN	H	51	20	71	59	6	65	267	101	119	220	312	579
2016	MN	L	32	26	57	9	68	76	339	83	51	134	468	807
2016	MO	HA	12	14	26	19	0	19	276	65	170	234	357	633
2016	MO	HB	24	29	53	76	5	80	223	32	142	173	408	631
2016	MO	L	36	43	78	1	30	31	352	151	104	256	331	683
2016	ND	H	13	3	16	16	12	28	196	47	10	57	76	272
2016	ND	L	2	3	4	11	20	31	220	25	22	40	80	300
2016	NE	H	0	51	51	8	21	29	178	30	27	58	197	375
2016	NE	L	0	68	68	34	26	60	231	48	14	57	171	397
2016	WI	H	25	35	60	20	8	28	287	84	6	89	182	470
2016	WI	L	25	35	60	20	8	28	287	84	6	89	182	470

Table 8. The abundant and well-distributed of rainfall (AWDR) measured at different times during the growing season for eight state over a three year period (2014, 2015, and 2016) and two productivity sites (Prod. – high (H) and low (L) based on historical yield data) during ten days before N applied at at-planting (10dBPN), ten days after N applied at-planting (10dAPN), ten days before and after N applied at-planting (10dBAPN), ten days before N split-applied (10dBSN), ten days after N split-applied (10dASN), ten days before and after N split-applied (10dBASN), vegetative (Vege.), two weeks before VT (2wkBVT), two weeks after VT (2wkAVT), two weeks before and after VT (2wkBAVT), grain fill, and whole growing season.

			Periods during the growing season											
Year	State	Prod.	10d-BPN	10d-APN	10d-BAPN	10d-BSN	10d-ASN	10d-BASN	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season
			---------- AWDR ----------											
2014	IA	H	28	2	31	56	4	56	219	1	1	1	72	307
2014	IA	L	20	14	42	56	63	122	246	24	1	4	243	522
2014	IL	H	0	27	21	19	42	76	291	69	35	164	162	482
2014	IL	L	4	37	33	43	0	39	160	1	19	29	179	367
2014	IN	H	29	8	45	96	26	110	231	20	17	35	94	337
2014	IN	L	45	4	53	105	25	118	239	15	16	28	85	334
2014	MN	H	3	23	31	12	7	23	177	0	4	9	87	289
2014	MN	L	22	3	22	6	3	12	156	5	4	11	31	188
2014	MO	H	10	18	38	33	2	35	105	8	10	26	33	151
2014	MO	L	8	29	48	14	15	43	36	17	18	6	42	208
2014	ND	H	2	6	11	22	18	38	100	2	0	6	57	172
2014	ND	L	3	9	16	6	0	9	111	1	0	0	49	176
2014	NE	H	24	21	62	28	15	57	170	30	16	10	145	345
2014	NE	L	7	25	39	14	9	29	206	1	0	5	122	349
2014	WI	H	22	13	46	67	33	119	200	2	9	15	113	335
2014	WI	L	22	20	58	64	54	150	234	1	3	6	81	326

Table 8. Continued.

Year	State	Prod.	Periods during the growing season											
			10d-BPN	10d-APN	10d-BAPN	10d-BSN	10d-ASN	10d-BASN	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season
			------------------------------ AWDR ------------------------------											
2015	IA	H	0	16	19	11	30	51	206	37	8	50	105	339
2015	IA	L	24	21	53	7	10	27	222	33	12	68	179	435
2015	IL	H	7	2	10	34	38	87	203	72	9	70	72	294
2015	IL	L	7	0	13	30	60	116	237	37	10	51	90	358
2015	IN	H	8	11	30	2	2	5	143	83	0	72	43	197
2015	IN	L	8	11	26	2	2	5	142	57	0	50	46	203
2015	MN	H	8	3	16	35	13	67	249	23	39	79	190	474
2015	MN	L	20	12	28	17	3	25	207	27	12	54	113	345
2015	MO	H	11	3	21	7	63	66	198	46	48	115	85	306
2015	MO	L	10	12	30	75	10	90	365	88	10	120	91	488
2015	ND	H	2	5	10	13	30	57	246	33	10	53	23	275
2015	ND	L	1	0	2	21	31	59	158	29	11	38	33	198
2015	NE	H	3	13	19	12	2	15	273	12	12	33	31	315
2015	NE	L	10	8	24	0	10	9	165	6	36	53	96	287
2015	WI	H	6	13	20	8	0	8	191	9	0	8	107	326
2015	WI	L	8	17	26	22	1	26	169	17	0	1	39	216

Table 8. Continued.

Year	State	Prod.	10d-BPN	10d-APN	10d-BAPN	10d-BSN	10d-ASN	10d-BASN	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season
			Periods during the growing season											
			AWDR											
2016	IA	H	27	15	49	1	13	17	219	87	3	84	100	353
2016	IA	L	10	15	32	2	40	41	150	41	3	46	224	401
2016	IL	H	4	21	30	0	57	69	230	31	27	71	206	467
2016	IL	L	40	54	83	4	0	3	216	45	29	95	193	443
2016	IN	H	14	0	14	6	1	9	78	66	1	67	245	338
2016	IN	L	14	0	13	4	1	7	72	59	1	64	263	357
2016	MN	H	26	9	41	39	3	39	187	64	32	122	182	397
2016	MN	L	18	7	31	2	24	30	213	46	19	78	302	550
2016	MO	HA	8	6	17	7	0	6	169	16	103	137	230	426
2016	MO	HB	13	11	30	41	2	36	144	13	84	103	257	423
2016	MO	L	18	22	49	0	10	9	216	66	43	140	218	467
2016	ND	H	4	1	6	7	4	15	116	15	3	22	38	168
2016	ND	L	0	1	1	2	6	12	133	15	10	24	42	189
2016	NE	H	0	33	26	0	7	11	92	10	4	24	111	228
2016	NE	L	0	45	36	9	5	25	142	25	8	32	104	262
2016	WI	H	12	21	39	4	2	10	181	32	2	34	116	319
2016	WI	L	12	21	39	3	2	10	181	32	2	34	116	319

Table 9. Analysis of variance for six N response trials conducted in Indiana over a three year period (2014, 2015, and 2016) for response variables of grain dry matter (GDM), physiological maturity plant N content (PMN), and internal N efficiency (IE = GDM/PMN). Treatments included two productivity sites (Prod – low and high: based on historical data) within year, N rates (NR) from 0 to 315 kg N ha-1 in 45 kg N ha-1, two N application timing (T - all 'at-planting' or 'split' with 45 kg N ha-1 at planting and the remainder at V9±1 V-stage). The linear and quadratic effects of NR (NRL and NRQ) were evaluated at 90 to 315 kg N ha-1 in 45 kg N ha-1 increments for at-planting and split timings. The significance of a 2- or 3-way interaction was used over the main effects. Likewise, significant 3-way interactions were used over 2-way interactions.

	GDM				PMN					IE				
	14	15	16		14		15		16	14		15	16	
	Combined†		Low‡	High‡	Low	High	Low	High	Combined	Low	High	Combined	Low	High
Source of variation	---------- Level of significance ----------													
Prod.	*	*	-	-	-	-	-	-	*	-	-	*	-	-
NR	*	*	*	*	*	*	*	*	*	*	*	*	*	*
NR_L	*	*	*	*	*	*	*	*	*	*	*	*	*	*
NR_Q	*	*	ns	*	*	*	*	ns	*	*	*	*	*	ns
T	*	*	ns	ns	*	ns	ns	*	*	ns	ns	ns	ns	*
NR*T														
NR_L*T	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	*	ns
NR_Q*T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Prod.*NR														
Prod.*NR_L	ns	*	-	-	-	-	-	-	*	-	-	*	-	-
Prod.*NR_Q	ns	*	-	-	-	-	-	-	ns	-	-	ns	-	-
Prod.*T	ns	*	-	-	-	-	-	-	*	-	-	*	-	-
Prod.*NR_L*T	ns	*	-	-	-	-	-	-	*	-	-	ns	-	-
Prod.*NR_Q*T	ns	ns	-	-	-	-	-	-	ns	-	-	*	-	-

* Significant = $p \leq 0.10$

† State-years where a combined analysis could be performed due to homogenous errors between productivity sites.

‡ Sites with significant treatment effects for state-years where a combined analysis could not be conducted due to non-homogeneous errors.

Table 10. Internal N efficiency (IE = grain dry matter/total plant N content at maturity) response to N rate (0 to 315 kg N ha-1 in 45 kg N ha-1 increments) and timing (T - all 'at-planting (AP)' or 'split (S)' with 45 or 90 kg N ha-1 at planting and the remainder at V9±1 V-stage) at two productivity site (Prod – high (H) and low (L) based on historical yield data) in eight states over a three year period (2014, 2015, and 2016). Predicted values of IE were calculated at the economic optimum N rate (EONR) (± standard error) for each productivity site and timing. Upper and lower 95% confidence limits (U and L CLM) were calculated for around the EONR and IE at EONR (IEE). Regression coefficients and IEE were considered non-significant if followed by (ns) and significant when not noted. Within a productivity-state-year differences between N application timings were noted by letters (a and b) for regression coefficients and IEE.

Year	State	Prod.	T	Model†	Adj. R^2	a	bx	cx^2‡	IE_E	UCLM	LCLM	EONR	UCLM	LCLM
									----- kg GDM kg^{-1} -----			------ kg N ha^{-1} ------		
2014	IA	H	AP	*	0.65	62 ± 1	-0.048 ± 0.006	ns	54 ± 1	56	53	160	224	134
2014	IA	H	S	*	0.71	61 ± 1	-0.041 ± 0.005	ns	55 ± 0	56	54	153	224	131
2014	IA	L	AP	*	0.82	63 ± 1	-0.109 ± 0.017b	0.00018 ± 0.00005	50 ± 1b	51	48	160	194	165
2014	IA	L	S	*	0.63	61 ± 1	-0.044 ± 0.006a	ns	54 ± 1a	55	53	155	224	134
2015	IA	H	AP	*	0.69	60 ± 1	-0.057 ± 0.007a	ns	52 ± 1	54	51	130	179	.
2015	IA	H	S	*	0.32	60 ± 2	-0.126 ± 0.035b	0.00031 ± 0.00011	50 ± 1	53	47	107	154	90
2015	IA	L	AP	*	0.73	63 ± 1	-0.058 ± 0.006	ns	54 ± 1a	55	52	165	224	145
2015	IA	L	S	*	0.71	62 ± 1	-0.052 ± 0.006	ns	52 ± 1b	53	51	187	269	179
2016	IA	H	AP	*	0.33	51 ± 3	-0.058 ± 0.014	ns	46 ± 2	49	42	90	179	11
2016	IA	H	S	*	0.21	52 ± 2	-0.033 ± 0.011	ns	46 ± 1	48	43	190	.	.
2016	IA	L	AP	*	0.59	63 ± 1	-0.052 ± 0.008	ns	53 ± 1	55	52	186	269	172
2016	IA	L	S	*	0.53	62 ± 1	-0.045 ± 0.007	ns	54 ± 1	56	52	188	269	173
2014	IL	H	AP	*	0.52	70 ± 2	-0.050 ± 0.008	ns	59 ± 1b	61	57	226	314	.
2014	IL	H	S	*	0.41	71 ± 1	-0.034 ± 0.007	ns	62 ± 1a	64	60	263	.	.
2014	IL	L	AP	*	0.65	71 ± 1	-0.053 ± 0.007	ns	54 ± 1b	57	52	307	.	.
2014	IL	L	S	*	0.63	69 ± 1	-0.049 ± 0.007	ns	58 ± 1a	60	56	237	.	.
2015	IL	H	AP	*	0.44	70 ± 1	-0.038 ± 0.007	ns	60 ± 1	63	58	252	.	.
2015	IL	H	S	*	0.51	69 ± 1	-0.036 ± 0.006	ns	61 ± 1	62	59	238	314	.
2015	IL	L	AP	*	0.33	55 ± 2	0.103 ± 0.029	-0.00034 ± 0.00009	63 ± 1	65	60	141	.	.
2015	IL	L	S	*	0.42	55 ± 2	0.123 ± 0.028	-0.00039 ± 0.00008	65 ± 1	67	62	124	.	.
2016	IL	H	AP	*	0.75	69 ± 1	-0.049 ± 0.005b	ns	59 ± 1b	60	57	205	269	191
2016	IL	H	S	*	0.67	68 ± 1	-0.033 ± 0.004a	ns	62 ± 0a	63	61	177	269	159
2016	IL	L	AP	*	0.66	68 ± 1	-0.057 ± 0.007a	ns	55 ± 1	57	54	228	293	224
2016	IL	L	S	*	0.68	70 ± 2	-0.109 ± 0.028b	0.00015 ± 0.00008	56 ± 1	59	54	164	221	166

Table 10 Continued.

Year	State	Prod.	T	Model§	Adj. R^2	a	bx	cx^2	IE_E	UCLM	LCLM	EONR	UCLM	LCLM
									----- kg GDM kg^{-1} -----			------ kg N ha^{-1} ------		
2014	IN	H	AP	*	0.84	65 ± 1	-0.065 ± 0.005	ns	55 ± 1	56	54	159	200	159
2014	IN	H	S	*	0.78	65 ± 1	-0.060 ± 0.006	ns	54 ± 1	56	53	172	224	171
2014	IN	L	AP	*	0.66	60 ± 1	-0.056 ± 0.007	ns	50 ± 1	51	48	211	269	179
2014	IN	L	S	*	0.79	61 ± 1	-0.062 ± 0.006	ns	49 ± 1	50	48	215	269	192
2015	IN	H	AP	*	0.69	65 ± 2	-0.086 ± 0.010	ns	55 ± 1a	58	53	108	179	.
2015	IN	H	S	*	0.78	63 ± 2	-0.087 ± 0.008	ns	49 ± 1b	51	48	160	224	153
2015	IN	L	AP	*	0.77	68 ± 1	-0.073 ± 0.007	ns	52 ± 1b	54	50	222	269	222
2015	IN	L	S	*	0.75	68 ± 1	-0.065 ± 0.007	ns	55 ± 1a	57	53	206	269	198
2016	IN	H	AP	*	0.85	74 ± 2	-0.122 ± 0.022b	0.00014 ± 0.00007	58 ± 1b	60	56	162	196	159
2016	IN	H	S	*	0.61	73 ± 2	-0.068 ± 0.010a	ns	63 ± 1a	65	61	151	224	.
2016	IN	L	AP	*	0.87	67 ± 1	-0.091 ± 0.016a	0.00009 ± 0.00005b	56 ± 1a	58	55	132	164	130
2016	IN	L	S	*	0.75	67 ± 1	-0.151 ± 0.020b	0.00034 ± 0.00006a	54 ± 1b	56	52	119	142	119
2014	MN	H	AP	*	0.68	69 ± 1	-0.053 ± 0.008b	ns	59 ± 1b	61	57	176	269	177
2014	MN	H	S	*	0.42	68 ± 1	-0.031 ± 0.008a	ns	63 ± 1a	64	61	158	.	134
2014	MN	L	AP	*	0.9	69 ± 1	-0.115 ± 0.016	0.00014 ± 0.00005	56 ± 1b	57	54	147	175	149
2014	MN	L	S	*	0.82	69 ± 1	-0.113 ± 0.018	0.00019 ± 0.00006	58 ± 1a	60	57	117	142	114
2015	MN	H	AP	*	0.72	69 ± 2	-0.141 ± 0.023	0.00030 ± 0.00007	58 ± 1	60	56	99	122	90
2015	MN	H	S	*	0.51	69 ± 2	-0.140 ± 0.028	0.00034 ± 0.00008	56 ± 1	58	53	151	193	134
2015	MN	L	AP	*	0.55	53 ± 1	-0.037 ± 0.006	ns	46 ± 1b	47	45	197	.	179
2015	MN	L	S	*	0.31	54 ± 1	-0.025 ± 0.006	ns	49 ± 1a	51	48	166	.	134
2016	MN	H	AP	*	0.16	64 ± 3	0.109 ± 0.040	-0.00031 ± 0.00012	73 ± 2a	76	70	240	.	.
2016	MN	H	S	*	0.46	66 ± 3	0.083 ± 0.038	-0.00040 ± 0.00012	57 ± 2b	61	53	285	.	.
2016	MN	L	AP	*	0.73	73 ± 1	-0.055 ± 0.006	ns	60 ± 1b	61	58	234	300	224
2016	MN	L	S	*	0.66	72 ± 1	-0.044 ± 0.006	ns	65 ± 1a	66	63	167	224	162

Table 10. Continued.

Year	State	Prod.	T	Model§	Adj. R^2	a	bx	cx^2	IE_E	UCLM	LCLM	EONR	UCLM	LCLM
									----- kg GDM kg^{-1} -----			------ kg N ha^{-1} ------		
2014	MO	H	AP	*	0.59	53 ± 1	-0.052 ± 0.008	ns	41 ± 1b	43	39	224	293	214
2014	MO	H	S	*	0.49	52 ± 1	-0.040 ± 0.007	ns	44 ± 1a	46	43	188	268	179
2014	MO	L	AP	*	0.51	50 ± 1	-0.034 ± 0.006	ns	42 ± 1b	44	41	241	.	.
2014	MO	L	S	*	0.31	50 ± 1	-0.022 ± 0.006	ns	46 ± 1a	47	45	177	.	.
2015	MO	H	AP	ns	0.05	56 ± 3	-0.022 ± 0.014ns	ns	52 ± 2	55	46	272	.	.
2015	MO	H	S	ns	-0.03	55 ± 3	0.007 ± 0.016ns	ns	56 ± 1	64	51	314	.	.
2015	MO	L	AP	ns	0.09	48 ± 3	0.035 ± 0.018b	ns	59 ± 3a	66	52	314	0	.
2015	MO	L	S	*	0.23	44 ± 4	0.174 ± 0.052a	-0.00052 ± 0.00016	48 ± 3b	55	41	314	.	.
2016	MO	HA	AP	*	0.57	52 ± 2	-0.055 ± 0.008a	ns	38 ± 1	41	36	239	310	224
2016	MO	HA	S	*	0.59	54 ± 2	-0.136 ± 0.027b	0.00030 ± 0.00008	38 ± 1	40	36	205	247	179
2016	MO	HB	AP	*	0.71	55 ± 1	-0.066 ± 0.008	ns	38 ± 1b	40	36	258	.	219
2016	MO	HB	S	*	0.79	56 ± 1	-0.069 ± 0.006	ns	42 ± 1a	43	40	207	269	207
2016	MO	L	AP	*	0.69	63 ± 2	-0.120 ± 0.028b	0.00018 ± 0.00009	48 ± 1	51	46	164	214	163
2016	MO	L	S	*	0.75	61 ± 1	-0.063 ± 0.006a	ns	49 ± 1	51	48	191	269	179
2014	ND	H	AP	*	0.32	59 ± 2	-0.043 ± 0.011	ns	51 ± 1	54	49	171	269	.
2014	ND	H	S	*	0.13	58 ± 2	-0.029 ± 0.012	ns	53 ± 1	56	50	164	.	.
2014	ND	L	AP	*	0.15	58 ± 4	-0.048 ± 0.019	ns	50 ± 2	54	46	177	314	.
2014	ND	L	S	*	0.28	57 ± 2	-0.048 ± 0.013	ns	49 ± 1	52	46	165	269	.
2015	ND	H	AP	§	.	.	.	.	.	.	.	192	.	.
2015	ND	H	S	.	.	.	.	.	.	.	.	155	.	.
2015	ND	L	AP	.	.	.	.	.	.	.	.	101	.	.
2015	ND	L	S	.	.	.	.	.	.	.	.	139	.	.
2016	ND	H	AP	*	0.34	56 ± 1	-0.019 ± 0.005	ns	56 ± 1	58	54	45	134	.
2016	ND	H	S	*	0.19	55 ± 1	-0.016 ± 0.006	ns	55 ± 1	57	53	45	51	.
2016	ND	L	AP	ns	-0.01	52 ± 2	-0.011 ± 0.013ns	ns	50 ± 1	57	47	0	179	.
2016	ND	L	S	*	0.15	52 ± 2	-0.030 ± 0.012	ns	52 ± 2	56	47	0	90	.

Table 10. Continued.

Year	State	Prod.	T	Model§	Adj. R^2	a	bx	cx^2	IE_E	UCLM	LCLM	EONR	UCLM	LCLM
									----- kg GDM kg^{-1} -----			------ kg N ha^{-1} ------		
2014	NE	H	AP	*	0.45	53 ± 1	-0.034 ± 0.007		50 ± 1a	52	48	114	179	.
2014	NE	H	S	*	0.36	52 ± 1	-0.029 ± 0.007	ns	48 ± 1b	49	46	157	264	134
2014	NE	L	AP	*	0.23	64 ± 2	-0.027 ± 0.008	ns	56 ± 1	59	53	307	.	.
2014	NE	L	S	*	0.38	63 ± 1	-0.035 ± 0.008	ns	56 ± 1	58	54	217	.	.
2015	NE	H	AP	*	0.48	50 ± 1	-0.029 ± 0.005	ns	49 ± 1	51	47	46	59	.
2015	NE	H	S	*	0.42	49 ± 1	-0.022 ± 0.005	ns	49 ± 1	50	47	46	72	.
2015	NE	L	AP	*	0.18	60 ± 1	0.019 ± 0.007a	ns	66 ± 1a	68	63	314	0	.
2015	NE	L	S	*	0.13	64 ± 2	-0.021 ± 0.009b	ns	60 ± 1b	62	58	210	314	.
2016	NE	H	AP	*	0.53	73 ± 2	-0.131 ± 0.028	0.000297 ± 0.000085	69 ± 1	71	66	56	57	15
2016	NE	H	S	*	0.55	74 ± 2	-0.150 ± 0.029	0.000355 ± 0.000088	69 ± 1	72	67	56	55	17
2016	NE	L	AP	*	0.4	71 ± 3	-0.073 ± 0.016	ns	58 ± 2b	61	55	185	274	134
2016	NE	L	S	*	0.51	74 ± 3	-0.080 ± 0.014	ns	62 ± 1a	65	59	163	269	134
2014	WI	H	AP	*	0.35	55 ± 2	-0.075 ± 0.024b	0.000159 ± 0.000074	49 ± 1b	51	47	102	165	87
2014	WI	H	S	*	0.35	55 ± 1	-0.029 ± 0.007a	ns	53 ± 1a	55	51	77	179	.
2014	WI	L	AP	*	0.6	60 ± 2	-0.091 ± 0.024	0.000154 ± 0.000073	51 ± 1	53	49	139	199	134
2014	WI	L	S	*	0.6	59 ± 1	-0.084 ± 0.021	0.000144 ± 0.000065	51 ± 1	53	49	119	171	115
2015	WI	H	AP	*	0.43	54 ± 2	-0.071 ± 0.023b	0.000133 ± 0.000070	54 ± 2	57	51	0	31	.
2015	WI	H	S	*	0.27	51 ± 1	-0.021 ± 0.006a	ns	51 ± 1	53	49	0	34	.
2015	WI	L	AP	*	0.87	63 ± 1	-0.124 ± 0.016	0.000202 ± 0.000048	45 ± 1b	46	43	268	.	269
2015	WI	L	S	*	0.75	62 ± 1	-0.088 ± 0.019	0.000126 ± 0.000057	51 ± 1a	52	49	174	238	179
2016	WI	H	AP	*	0.85	64 ± 1	-0.156 ± 0.020	0.000277 ± 0.000061	50 ± 1	52	48	107	173	150
2016	WI	H	S	*	0.68	63 ± 1	-0.115 ± 0.021	0.000230 ± 0.000065	51 ± 1	53	49	144	202	166
2016	WI	L	AP	*	0.78	67 ± 2	-0.135 ± 0.028	0.000185 ± 0.000087	58 ± 1	60	56	73	104	67
2016	WI	L	S	*	0.76	67 ± 2	-0.150 ± 0.024	0.000287 ± 0.000074	57 ± 1	59	55	79	104	78

Level of significance for the regression model. ns = not significant, * = $p \leq 0.10$

† Not significant model, intercept, and/or slope IE_E was reported as the average IE across all N rates used in the model.

‡ Quadratic coefficient non-significant (ns) then linear regression was used.

§ Grain N concentration was not taken at ND in 2015.

Table 11. Grain dry matter (GDM) response to N rate (0 to 315 kg N ha-1 in 45 kg N ha-1 increments) and timing (T - all 'at-planting (AP)' or 'split (S)' with 45 or 90 kg N ha-1 at planting and the remainder at V9±1 V-stage) at two productivity sites (Prod - high (H) and low (L) based on historical yield data) in eight states over a three year period (2014, 2015, and 2016). Predicted values of GDM were calculated at the economic and agronomic optimum N rate (EONR and AONR, respectively) (± standard error) for each productivity site and timing. Regression coefficients and GDM at the EONR (GDME) were considered non-significant if followed by (ns) and significant when not noted. Within a productivity-state-year differences between N application timings were noted by letters (a and b) for regression coefficients and GDME.

Year	St.	Prod.	T	Model†	Adj. R^2	a	bx	cx^2‡	GDM_E	GDM_A	EONR	AONR
									-------- kg DM ha^{-1} --------		-- kg N ha^{-1} --	
2014	IA	H	AP	*	0.91	4337 ± 333	76.64 ± 8.79	-0.2236 ± 0.0453	10878 ± 149a‡	10905 ± 172a	160	171
2014	IA	H	S	*	0.89	4357 ± 357	74.49 ± 9.93	-0.2269 ± 0.0535	10444 ± 158b	10470 ± 183b	153	164
2014	IA	L	AP	*	0.91	7123 ± 259	57.55 ± 6.66	-0.1638 ± 0.0334	12141 ± 116	12179 ± 135	160	176
2014	IA	L	S	*	0.93	7027 ± 234	64.36 ± 6.36	-0.1923 ± 0.0336	12382 ± 104	12413 ± 121	155	167
2015	IA	H	AP	*	0.70	5228 ± 505	67.47 ± 16.81	-0.2402 ± 0.1063	9942 ± 214	9966 ± 239	130	140
2015	IA	H	S	*	0.76	5143 ± 435	81.50 ± 18.23	-0.3589 ± 0.1443	9751 ± 177	9768 ± 194	107	114
2015	IA	L	AP	*	0.90	4263 ± 350	74.10 ± 8.97	-0.2102 ± 0.0448	10766 ± 158	10793 ± 183	165	176
2015	IA	L	S	*	0.94	4388 ± 272	64.95 ± 6.11	-0.1608 ± 0.0269	10912 ± 131	10947 ± 159	187	202
2016	IA	H	AP	*	0.80	6240 ± 316	79.57 ± 16.59	-0.4150 ± 0.1573b	10038 ± 128b	10053 ± 133b	90	96
2016	IA	H	S	*	0.87	6412 ± 362	57.32 ± 7.89	-0.1384 ± 0.0339a	12305 ± 174a	12347 ± 215a	190	207
2016	IA	L	AP	*	0.95	6416 ± 264	68.31 ± 5.99	-0.1708 ± 0.0266	13210 ± 127	13243 ± 153	186	200
2016	IA	L	S	*	0.95	6531 ± 252	64.55 ± 5.60	-0.1585 ± 0.0245	13066 ± 121	13102 ± 148	188	204
2014	IL	H	AP	*	0.90	4048 ± 380	61.46 ± 7.05	-0.1255 ± 0.0260	11530 ± 208b	11575 ± 264b	226	245
2014	IL	H	S	*	0.94	4065 ± 323	58.56 ± 5.22	-0.1024 ± 0.0171	12383 ± 210a	12437 ± 278a	263	286
2014	IL	L	AP	*	0.79	3748 ± 481	38.05 ± 7.15	-0.0544 ± 0.0219	10303 ± 443	10333 ± 481	307	314
2014	IL	L	S	*	0.83	3598 ± 504	55.48 ± 8.80	-0.1070 ± 0.0309	10742 ± 285	10794 ± 371	237	259
2015	IL	H	AP	*	0.94	5860 ± 246	46.72 ± 4.03	-0.0834 ± 0.0133	12340 ± 146a	12406 ± 203	252	280
2015	IL	H	S	*	0.94	5853 ± 239	46.67 ± 4.10	-0.0883 ± 0.0141	11955 ± 133b	12018 ± 179	238	264
2015	IL	L	AP	*	0.74	4752 ± 620	77.50 ± 18.70	-0.2566 ± 0.1084	10575 ± 242a	10602 ± 275a	141	151
2015	IL	L	S	*	0.62	4769 ± 680	76.34 ± 22.38	-0.2880 ± 0.1458	9807 ± 254b	9828 ± 278b	124	133
2016	IL	H	AP	*	0.90	6101 ± 331	56.60 ± 6.67	-0.1264 ± 0.0267	12394 ± 177	12439 ± 223	205	224
2016	IL	H	S	*	0.94	5950 ± 269	66.95 ± 6.39	-0.1751 ± 0.0297	12318 ± 125	12350 ± 150	177	191
2016	IL	L	AP	*	0.87	5850 ± 355	47.43 ± 6.37	-0.0938 ± 0.0229	11789 ± 191a	11848 ± 255a	228	253
2016	IL	L	S	*	0.79	5967 ± 354	46.54 ± 8.80	-0.1275 ± 0.0426	10169 ± 162b	10214 ± 189b	164	183

Table 11. Continued.

Year	St.	Prod.	T	Model†	Adj. R^2	a	bx	cx^2	GDM_E	GDM_A	EONR	AONR
									-------- kg DM ha^{-1} --------		-- kg N ha^{-1} --	
2014	IN	H	AP	*	0.93	6122 ± 234	58.51 ± 6.14	-0.1693 ± 0.0314	11143 ± 105b	11177 ± 122b	159	173
2014	IN	H	S	*	0.92	6141 ± 275	59.75 ± 6.68	-0.1595 ± 0.0316	11698 ± 126a	11736 ± 151a	172	187
2014	IN	L	AP	*	0.87	6974 ± 300	45.49 ± 6.45	-0.1082 ± 0.0273	11701 ± 144b	11753 ± 180	211	233
2014	IN	L	S	*	0.89	6930 ± 289	48.89 ± 6.13	-0.1150 ± 0.0256	12078 ± 140a	12128 ± 174	215	236
2015	IN	H	AP	*	0.59	4339 ± 393	48.36 ± 15.30	-0.2009 ± 0.1135	7220 ± 172b	7249 ± 177b	108	120
2015	IN	H	S	*	0.75	4272 ± 422	51.03 ± 10.82	-0.1446 ± 0.0540	8735 ± 191a	8775 ± 221a	160	176
2015	IN	L	AP	*	0.92	4970 ± 372	65.37 ± 7.04	-0.1365 ± 0.0265	12758 ± 201	12799 ± 252	222	240
2015	IN	L	S	*	0.92	4835 ± 384	75.41 ± 7.83	-0.1713 ± 0.0316	13100 ± 197	13133 ± 235	206	220
2016	IN	H	AP	*	0.93	5906 ± 319	80.08 ± 8.38	-0.2324 ± 0.0429	12778 ± 144	12805 ± 166	162	172
2016	IN	H	S	*	0.94	5876 ± 277	82.35 ± 7.86	-0.2556 ± 0.0432	12486 ± 122	12510 ± 141	151	161
2016	IN	L	AP	*	0.80	8509 ± 379	65.38 ± 12.42	-0.2295 ± 0.0775	13141 ± 161	13166 ± 181	132	142
2016	IN	L	S	*	0.86	8482 ± 305	69.96 ± 11.07	-0.2725 ± 0.0765	12951 ± 128	12973 ± 139	119	128
2014	MN	H	AP	*	0.65	5260 ± 509	37.63 ± 11.41	-0.0932 ± 0.0503	8999 ± 241a	9059 ± 297a	176	202
2014	MN	H	S	*	0.68	5372 ± 365	30.92 ± 8.86	-0.0825 ± 0.0419	8200 ± 179b	8271 ± 201b	158	188
2014	MN	L	AP	*	0.75	5092 ± 509	63.94 ± 14.42	-0.2010 ± 0.0791	10149 ± 198	10178 ± 226	147	159
2014	MN	L	S	*	0.91	4953 ± 276	80.23 ± 9.59	-0.3203 ± 0.0664	9959 ± 100	9978 ± 109	117	125
2015	MN	H	AP	*	0.87	7818 ± 285	82.06 ± 13.52	-0.3908 ± 0.1165	12110 ± 118	12126 ± 123	99	105
2015	MN	H	S	*	0.76	8100 ± 377	49.43 ± 10.25	-0.1478 ± 0.0542	12192 ± 169	12232 ± 194	151	167
2015	MN	L	AP	*	0.88	8016 ± 247	36.97 ± 4.92	-0.0818 ± 0.0194	12124 ± 122	12192 ± 155	197	226
2015	MN	L	S	*	0.80	7998 ± 315	41.05 ± 7.60	-0.1090 ± 0.0358	11810 ± 146	11862 ± 174	166	188
2016	MN	H	AP	*	0.68	2603 ± 641	46.56 ± 10.88	-0.0873 ± 0.0372	8744 ± 359b	8807 ± 482b	240	267
2016	MN	H	S	*	0.92	2201 ± 435	64.70 ± 6.61	-0.1055 ± 0.0206	12073 ± 324a	12125 ± 420a	285	307
2016	MN	L	AP	*	0.90	6288 ± 355	53.44 ± 6.26	-0.1040 ± 0.0222	13102 ± 198a	13155 ± 259a	234	257
2016	MN	L	S	*	0.86	6062 ± 419	70.90 ± 10.55	-0.1973 ± 0.0517	12399 ± 190b	12430 ± 221b	167	180

Table 11. Continued.

Year	St.	Prod.	T	Model†	Adj. R^2	a	bx	cx^2	GDM_E	GDM_A	EONR	AONR
									-------- kg DM ha^{-1} --------		-- kg N ha^{-1} --	
2014	MO	H	AP	*	0.87	6080 ± 400	54.06 ± 7.48	-0.1102 ± 0.0280	12661 ± 234a	12712 ± 309	224	245
2014	MO	H	S	*	0.79	5861 ± 518	61.46 ± 11.52	-0.1511 ± 0.0504	12074 ± 248b	12111 ± 304	188	203
2014	MO	L	AP	*	0.90	5035 ± 333	50.24 ± 5.67b	-0.0945 ± 0.0194a	11654 ± 189	11713 ± 250	241	266
2014	MO	L	S	*	0.91	4728 ± 344	71.88 ± 8.22a	-0.1888 ± 0.0383b	11538 ± 161	11569 ± 192	177	190
2015	MO	H	AP	*	0.75	2938 ± 545	41.24 ± 8.40a	-0.0671 ± 0.0263b	9193 ± 372	9275 ± 545	272	307
2015	MO	H	S	*	0.73	3286 ± 499	20.56 ± 7.54b	-0.0047 ± 0.0236ans	9276 ± 547	9279 ± 548	314	314
2015	MO	L	AP	*	0.53	2304 ± 615	18.87 ± 8.94b	-0.0129 ± 0.0274ns	6959 ± 597b	6961 ± 599b	314	314
2015	MO	L	S	*	0.84	1534 ± 506	44.28 ± 7.36a	-0.0616 ± 0.0225	9359 ± 492a	9360 ± 493a	314	314
2016	MO	HA	AP	*	0.95	7538 ± 227	46.56 ± 3.86	-0.0875 ± 0.0132	13671 ± 127a	13734 ± 170a	239	266
2016	MO	HA	S	*	0.93	7520 ± 247	51.03 ± 4.92	-0.1130 ± 0.0194	13232 ± 123b	13282 ± 155b	205	226
2016	MO	HB	AP	*	0.92	5979 ± 295	45.60 ± 4.74	-0.0793 ± 0.0155	12462 ± 181a	12531 ± 256a	258	287
2016	MO	HB	S	*	0.93	5894 ± 240	47.70 ± 4.72	-0.1036 ± 0.0183	11332 ± 121b	11386 ± 155b	207	230
2016	MO	L	AP	*	0.82	5697 ± 387	55.92 ± 9.78	-0.1561 ± 0.0481	10668 ± 175b	10705 ± 203b	164	179
2016	MO	L	S	*	0.89	5705 ± 327	54.64 ± 7.04	-0.1302 ± 0.0299	11393 ± 158a	11436 ± 196a	191	210
2014	ND	H	AP	*	0.76	4940 ± 508	60.29 ± 12.37	-0.1616 ± 0.0588	10524 ± 233	10561 ± 277	171	186
2014	ND	H	S	*	0.79	4958 ± 455	61.95 ± 11.56	-0.1741 ± 0.0572	10436 ± 205	10469 ± 238	164	178
2014	ND	L	AP	*	0.56	1732 ± 510	35.59 ± 11.30	-0.0871 ± 0.0492	5302 ± 244	5366 ± 300	177	204
2014	ND	L	S	*	0.63	1700 ± 432	37.51 ± 10.37	-0.0991 ± 0.0486	5191 ± 202	5248 ± 239	165	189
2015	ND	H	AP	*	0.62	4477 ± 589	44.47 ± 12.30	-0.1032 ± 0.0508	9211 ± 285	9267 ± 358	192	215
2015	ND	H	S	*	0.61	4239 ± 670	62.24 ± 18.10	-0.1850 ± 0.0950	9445 ± 297	9476 ± 346	155	168
2015	ND	L	AP	*	0.60	3477 ± 712	99.49 ± 32.38	-0.4658 ± 0.2741	8775 ± 285	8789 ± 312	101	107
2015	ND	L	S	*	0.67	3762 ± 525	60.13 ± 16.11	-0.1991 ± 0.0948	8273 ± 226	8301 ± 259	139	151
2016	ND	H	AP	ns	-0.06	9173 ± 571	34.60 ± 37.38ns	-1.0598 ± .ns	9419 ± 70	9419 ± 70	45	45
2016	ND	H	S	ns	-0.06	9173 ± 675	38.66 ± 39.56ns	-1.0598 ± .ns	9481 ± 115	9481 ± 115	45	45
2016	ND	L	AP	ns	0.00	7576 ± 425	52.50 ± 18.33	-1.0598 ± .ns	8145 ± 128	8145 ± 128	0	0
2016	ND	L	S	ns	0.02	7576 ± 361	51.24 ± 15.97	-1.0598 ± .ns	8118 ± 105	8118 ± 105	0	0

Table 11. Continued.

Year	St.	Prod.	T	Model†	Adj. R^2	a	bx	cx^2	GDM_E	GDM_A	EONR	AONR
									-------- kg DM ha^{-1} --------		-- kg N ha^{-1} --	
2014	NE	H	AP	*	0.75	11551 ± 199	37.97 ± 8.83	-0.1744 ± 0.0732	13585 ± 95	13618 ± 88	114	128
2014	NE	H	S	*	0.71	11674 ± 224	25.42 ± 5.97	-0.0747 ± 0.031	13760 ± 119	13838 ± 116	157	189
2014	NE	L	AP	*	0.46	7094 ± 907	35.96 ± 13.49	-0.0530 ± 0.0413ns	13095 ± 730	13164 ± 907	307	314
2014	NE	L	S	*	0.71	6698 ± 650	57.74 ± 13.07	-0.1295 ± 0.0521	13093 ± 325	13136 ± 401	217	235
2015	NE	H	AP	*	0.11	12096 ± 277	55.71 ± 11.26	-1.0598 ± .ns	12828 ± 105	12828 ± 105	46	48
2015	NE	H	S	*	0.19	12096 ± 231	56.69 ± 9.24	-1.0598 ± .ns	12854 ± 87	12854 ± 87	46	49
2015	NE	L	AP	*	0.68	4433 ± 477	16.42 ± 7.09b	0.0000 ± 0.0217ans	9589 ± 477b	9587 ± 476b	314	314
2015	NE	L	S	*	0.86	4057 ± 422	61.80 ± 8.83a	-0.1437 ± 0.0366b	10660 ± 209a	10699 ± 256a	210	227
2016	NE	H	AP	*	0.48	11763 ± 224	75.54 ± 6.72	-1.0598 ± .ns	13109 ± 85	13109 ± 85	56	59
2016	NE	H	S	*	0.46	11763 ± 229	75.09 ± 6.92	-1.0598 ± .ns	13093 ± 87	13093 ± 87	56	59
2016	NE	L	AP	*	0.78	9177 ± 417	49.95 ± 9.63	-0.1271 ± 0.0436	14041 ± 194	14085 ± 238	185	204
2016	NE	L	S	*	0.86	9038 ± 356	64.48 ± 9.59	-0.1910 ± 0.0502	14449 ± 158	14479 ± 184	163	176
2014	WI	H	AP	*	0.89	7256 ± 239	72.74 ± 10.49	-0.3320 ± 0.0863	11222 ± 97a	11241 ± 105a	102	110
2014	WI	H	S	*	0.85	7171 ± 260	91.21 ± 15.73	-0.5580 ± 0.1759	10887 ± 104b	10898 ± 106b	77	82
2014	WI	L	AP	*	0.83	7512 ± 238	40.99 ± 6.93	-0.1302 ± 0.0391	10695 ± 108	10740 ± 120	139	157
2014	WI	L	S	*	0.79	7476 ± 261	46.91 ± 9.16	-0.1766 ± 0.0610	10557 ± 117	10591 ± 119	119	133
2015	WI	H	AP	ns	-0.06	9884 ± 245	23.40 ± 23.68ns	-1.0598 ± .ns	9996 ± 90	9996 ± 90	0	0
2015	WI	H	S	ns	-0.05	9884 ± 279	33.94 ± 18.76	-1.0598 ± .ns	10117 ± 101	10117 ± 101	0	0
2015	WI	L	AP	*	0.48	7907 ± 455	17.64 ± 6.76	-0.0242 ± 0.0207ns	10897 ± 283	11063 ± 454	268	314
2015	WI	L	S	*	0.53	7835 ± 416	26.72 ± 8.88	-0.0632 ± 0.0374ns	10571 ± 211	10659 ± 250	174	211
2016	WI	H	AP	*	0.28	10818 ± 272	14.28 ± 3.96	-0.0449 ± 0.0121	11830 ± 159b	11954 ± 159b	107	159
2016	WI	H	S	*	0.68	10627 ± 241	23.73 ± 5.99	-0.0658 ± 0.0294	12677 ± 132a	12766 ± 123a	144	179
2016	WI	L	AP	*	0.11	7900 ± 635	39.47 ± 37.72ns	-0.2363 ± 0.4121ns	9523 ± 328	9548 ± 262	73	83
2016	WI	L	S	*	0.22	7900 ± 485	38.46 ± 27.03ns	-0.2139 ± 0.2726ns	9601 ± 254	9628 ± 195	79	89

Level of significance for the regression model. ns = not significant, * = $p \leq 0.10$

† Not significant model GDM_E was reported as the average GDM across all N rates used in the model.

Table 12. Physiological maturity N content (PMN) response to N rate (0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) and timing (T - all 'at-planting (AP)' or 'split (S)' with 45 or 90 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) at two productivity site (Prod. - high (H) and low (L) based on historical yield data) in eight states over a three year period (2014, 2015, and 2016). Predicted values of PMN were calculated at the economic optimum N rate (EONR) (± standard error) for each productivity site and timing. Upper and lower 95% confidence limits (U and L CLM) were calculated for around the EONR and PMN at the EONR (PMN_E). Regression coefficients and PMN_E were considered non-significant if followed by (ns) and significant when not noted. Within a productivity-state-year differences between N application timings were noted by letters (a and b) for regression coefficients and PMN_E.

Year	State	Prod.	T	Model†	Adj. R^2	a	bx	cx^2‡	PMN_E	UCLM	LCLM	EONR	UCLM	LCLM
									------------------------ kg N ha^{-1} ------------------------					
2014	IA	H	AP	*	0.91	73 ± 7	1.150 ± 0.106	-0.00213 ± 0.00032	202 ± 5a†	212	193	160	170	154
2014	IA	H	S	*	0.91	76 ± 6	1.081 ± 0.091	-0.00214 ± 0.00028	191 ± 4b	199	183	153	162	147
2014	IA	L	AP	*	0.92	114 ± 6	1.150 ± 0.096	-0.00216 ± 0.00030	243 ± 4	251	234	160	169	154
2014	IA	L	S	*	0.86	119 ± 8	1.003 ± 0.122	-0.00178 ± 0.00037	232 ± 5	243	221	155	168	146
2015	IA	H	AP	*	0.84	94 ± 9	0.931 ± 0.129	-0.00162 ± 0.00040b	188 ± 5	199	177	130	145	121
2015	IA	H	S	*	0.75	92 ± 10	1.251 ± 0.148	-0.00311 ± 0.00045	190 ± 6	202	178	107	118	98
2015	IA	L	AP	*	0.91	70 ± 8	1.116 ± 0.115	-0.00190 ± 0.00035	202 ± 5	212	192	165	176	157
2015	IA	L	S	*	0.96	73 ± 5	1.062 ± 0.075	-0.00171 ± 0.00023	211 ± 3	202	187	187	194	182
2016	IA	H	AP	*	0.56	130 ± 21	1.246 ± 0.313	-0.00236 ± 0.00096	223 ± 12b	248	199	90	118	77
2016	IA	H	S	*	0.78	131 ± 13	0.999 ± 0.198	-0.00139 ± 0.00061	270 ± 8a	287	254	190	215	178
2016	IA	L	AP	*	0.87	99 ± 10	1.242 ± 0.145	-0.00219 ± 0.00045	254 ± 6	267	242	186	198	178
2016	IA	L	S	*	0.87	103 ± 9	1.163 ± 0.135	-0.00210 ± 0.00041	248 ± 6	259	236	188	201	180
2014	IL	H	AP	*	0.89	61 ± 8	0.836 ± 0.116	-0.00106 ± 0.00035	196 ± 4	205	187	226	239	217
2014	IL	H	S	*	0.90	58 ± 7	0.848 ± 0.110	-0.00114 ± 0.00034	202 ± 4	211	193	263	275	254
2014	IL	L	AP	*	0.83	59 ± 7	0.452 ± 0.037b	ns‡	197 ± 7	211	184	307	.	.
2014	IL	L	S	*	0.83	49 ± 10	0.934 ± 0.146a	-0.00148 ± 0.00045	188 ± 6	199	176	237	252	228
2015	IL	H	AP	*	0.90	85 ± 6	0.689 ± 0.096	-0.00085 ± 0.00029	205 ± 4	213	198	252	265	243
2015	IL	H	S	*	0.89	85 ± 6	0.708 ± 0.092	-0.00100 ± 0.00028	197 ± 3	204	190	238	249	229
2015	IL	L	AP	*	0.65	99 ± 11	0.626 ± 0.155a	-0.00108 ± 0.00046	165 ± 6a	179	152	141	177	127
2015	IL	L	S	*	0.46	113 ± 8	0.215 ± 0.043b	ns	139 ± 5b	158	132	124	224	224
2016	IL	H	AP	*	0.90	89 ± 7	0.902 ± 0.104	-0.00144 ± 0.00033	213 ± 4a	222	205	205	217	197
2016	IL	H	S	*	0.91	92 ± 6	0.914 ± 0.084	-0.00170 ± 0.00026	200 ± 4b	208	193	177	187	171
2016	IL	L	AP	*	0.85	82 ± 9	0.916 ± 0.133	-0.00144 ± 0.00041	216 ± 5a	226	206	228	242	219
2016	IL	L	S	*	0.79	89 ± 9	0.754 ± 0.129	-0.00123 ± 0.00040	179 ± 6b	190	168	164	185	153

Table 12. Continued.

Year	State	Prod.	T	Model	Adj. R^2	a	bx	cx^2	PMN_E	UCLM	LCLM	EONR	UCLM	LCLM
									------------------------ kg N ha^{-1} ------------------------					
2014	IN	H	AP	*	0.94	92 ± 5	1.016 ± 0.080	-0.00178 ± 0.00025	209 ± 3	216	202	159	167	153
2014	IN	H	S	*	0.92	96 ± 7	0.967 ± 0.098	-0.00152 ± 0.00030	217 ± 4	226	209	172	183	165
2014	IN	L	AP	*	0.87	111 ± 9	1.000 ± 0.127	-0.00161 ± 0.00039	242 ± 5	253	231	211	202	179
2014	IN	L	S	*	0.91	113 ± 8	0.955 ± 0.120	-0.00126 ± 0.00037	250 ± 5	260	240	215	205	183
2015	IN	H	AP	*	0.69	80 ± 9	0.380 ± 0.045b	ns	121 ± 5b	132	111	108	179	179
2015	IN	H	S	*	0.90	67 ± 8	0.851 ± 0.124a	-0.00097 ± 0.00038	178 ± 5a	189	167	160	177	150
2015	IN	L	AP	*	0.93	65 ± 8	1.300 ± 0.125	-0.00207 ± 0.00038	252 ± 5	261	242	222	231	216
2015	IN	L	S	*	0.94	69 ± 7	1.253 ± 0.110	-0.00200 ± 0.00034	242 ± 4	251	233	206	215	200
2016	IN	H	AP	*	0.95	79 ± 6	1.259 ± 0.088a	-0.00225 ± 0.00027	224 ± 4a	231	216	162	169	156
2016	IN	H	S	*	0.90	85 ± 7	0.981 ± 0.108b	-0.00159 ± 0.00033a	197 ± 5b	206	188	151	163	143
2016	IN	L	AP	*	0.88	131 ± 8	0.988 ± 0.115	-0.00173 ± 0.00035b	231 ± 5	241	221	132	144	124
2016	IN	L	S	*	0.81	132 ± 9	1.174 ± 0.133	-0.00263 ± 0.00041	234 ± 5	246	223	119	131	111
2014	MN	H	AP	*	0.76	77 ± 9	0.613 ± 0.131	-0.00101 ± 0.00040	154 ± 6a	165	142	176	207	164
2014	MN	H	S	*	0.73	80 ± 6	0.473 ± 0.093	-0.00091 ± 0.00028	132 ± 4b	140	123	158	185	146
2014	MN	L	AP	*	0.87	74 ± 8	1.017 ± 0.117	-0.00191 ± 0.00035	182 ± 5a	192	172	147	159	139
2014	MN	L	S	*	0.88	80 ± 7	0.935 ± 0.100	-0.00184 ± 0.00030	164 ± 4b	172	156	117	127	110
2015	MN	H	AP	*	0.80	124 ± 8	0.942 ± 0.124	-0.00194 ± 0.00038	198 ± 5b	208	188	99	111	90
2015	MN	H	S	*	0.67	122 ± 10	0.955 ± 0.156	-0.00214 ± 0.00048	217 ± 7a	231	203	151	170	140
2015	MN	L	AP	*	0.85	146 ± 8	0.935 ± 0.127	-0.00161 ± 0.00039	268 ± 5a	279	258	197	211	188
2015	MN	L	S	*	0.70	147 ± 10	0.888 ± 0.155	-0.00178 ± 0.00048	245 ± 7b	259	232	166	188	155
2016	MN	H	AP	*	0.48	55 ± 10	0.278 ± 0.051b	ns	121 ± 7b	135	107	240	294	227
2016	MN	H	S	*	0.88	44 ± 7	0.604 ± 0.039a	ns	216 ± 6a	229	203	285	301	270
2016	MN	L	AP	*	0.87	86 ± 8	0.860 ± 0.121	-0.00121 ± 0.00037	221 ± 5a	230	211	234	248	226
2016	MN	L	S	*	0.85	90 ± 8	0.859 ± 0.116	-0.00149 ± 0.00035	192 ± 5b	202	181	167	182	158

Table 12 Continued.

Year	State	Prod.	T	Model	Adj. R^2	a	bx	cx^2	PMN_E	UCLM	LCLM	EONR	UCLM	LCLM
									------------------------ kg N ha^{-1} ------------------------					
2014	MO	H	AP	*	0.82	121 ± 16	1.163 ± 0.236	-0.00144 ± 0.00075	309 ± 9a	326	291	224	245	213
2014	MO	H	S	*	0.68	117 ± 20	1.256 ± 0.282	-0.00213 ± 0.00085	278 ± 11b	301	255	188	217	176
2014	MO	L	AP	*	0.85	115 ± 10	0.656 ± 0.051b	ns	273 ± 7a	287	260	241	260	230
2014	MO	L	S	*	0.85	100 ± 11	1.282 ± 0.162a	-0.00238 ± 0.00050	252 ± 7b	267	238	177	192	168
2015	MO	H	AP	*	0.77	64 ± 9	0.458 ± 0.046a	ns	189 ± 7a	204	174	272	301	257
2015	MO	H	S	*	0.75	60 ± 6	0.339 ± 0.036b	ns	167 ± 7b	180	153	314	.	.
2015	MO	L	AP	*	0.56	50 ± 8	0.242 ± 0.040b	ns	126 ± 7b	141	111	314	.	.
2015	MO	L	S	*	0.81	42 ± 8	0.491 ± 0.043a	ns	196 ± 8a	212	180	314	.	.
2016	MO	HA	AP	*	0.85	146 ± 15	1.235 ± 0.222	-0.00143 ± 0.00068b	359 ± 8a	376	342	239	257	229
2016	MO	HA	S	*	0.87	144 ± 11	1.592 ± 0.168	-0.00309 ± 0.00052	340 ± 7b	354	326	205	215	198
2016	MO	HB	AP	*	0.87	118 ± 11	0.819 ± 0.056	ns	329 ± 8a	345	312	258	276	246
2016	MO	HB	S	*	0.95	107 ± 7	0.979 ± 0.112	-0.00088 ± 0.00034a	272 ± 4b	281	263	207	219	200
2016	MO	L	AP	*	0.83	89 ± 10	1.170 ± 0.154	-0.00215 ± 0.00047	223 ± 7	237	210	164	178	155
2016	MO	L	S	*	0.90	95 ± 9	0.983 ± 0.128	-0.00135 ± 0.00039	234 ± 5	244	223	191	205	183
2014	ND	H	AP	*	0.66	93 ± 15	0.872 ± 0.219	-0.00133 ± 0.00067	204 ± 9	223	185	171	211	157
2014	ND	H	S	*	0.57	94 ± 15	0.939 ± 0.228	-0.00180 ± 0.00070	200 ± 10	220	180	164	201	150
2014	ND	L	AP	*	0.63	33 ± 10	0.579 ± 0.148	-0.00092 ± 0.00045	107 ± 6	120	94	177	217	163
2014	ND	L	S	*	0.55	32 ± 12	0.654 ± 0.176	-0.00117 ± 0.00054	108 ± 8	123	93	165	210	151
2015	ND	H	AP	§	.	.	.	.	.	.	.	192	.	.
2015	ND	H	S	.	.	.	.	.	.	.	.	155	.	.
2015	ND	L	AP	.	.	.	.	.	.	.	.	101	.	.
2015	ND	L	S	.	.	.	.	.	.	.	.	139	.	.
2016	ND	H	AP	ns	0.01	170 ± 8	0.050 ± 0.042ns	ns	178 ± 2	186	154	45	224	224
2016	ND	H	S	ns	0.01	172 ± 9	0.057 ± 0.050ns	ns	181 ± 3	191	153	45	179	179
2016	ND	L	AP	ns	-0.02	162 ± 10	0.030 ± 0.053ns	ns	167 ± 4	182	142	0	134	134
2016	ND	L	S	*	0.12	161 ± 8	0.100 ± 0.043	ns	161 ± 8	177	144	0	55	-48

Table 12. Continued.

Year	State	Prod.	T	Model	Adj. R^2	a	bx	cx^2	PMN_E	UCLM	LCLM	EONR	UCLM	LCLM
									------------------------ kg N ha^{-1} ------------------------					
2014	NE	H	AP	*	0.56	236 ± 8	0.288 ± 0.045b	ns	263 ± 5b	274	252	114	141	82
2014	NE	H	S	*	0.58	224 ± 11	0.679 ± 0.164a	-0.00127 ± 0.00050	294 ± 7a	308	280	157	173	124
2014	NE	L	AP	*	0.46	122 ± 15	0.408 ± 0.079b	ns	243 ± 14	270	215	307	.	.
2014	NE	L	S	*	0.69	105 ± 14	1.058 ± 0.205a	-0.00196 ± 0.00063	239 ± 8	256	222	217	228	193
2015	NE	H	AP	*	0.46	249 ± 8	0.226 ± 0.044	ns	255 ± 7	270	241	46	61	-1
2015	NE	H	S	*	0.38	253 ± 7	0.168 ± 0.038	ns	258 ± 6	270	245	46	63	1
2015	NE	L	AP	*	0.60	77 ± 6	0.221 ± 0.033b	ns	146 ± 6b	159	134	314	.	.
2015	NE	L	S	*	0.87	68 ± 7	0.914 ± 0.102a	-0.00175 ± 0.00031	180 ± 4a	189	172	210	210	191
2016	NE	H	AP	*	0.62	166 ± 6	0.536 ± 0.094	-0.00124 ± 0.00029	184 ± 4	193	175	56	52	21
2016	NE	H	S	*	0.63	162 ± 7	0.570 ± 0.101	-0.00128 ± 0.00031	181 ± 5	190	172	56	52	21
2016	NE	L	AP	*	0.72	124 ± 13	1.162 ± 0.198	-0.00227 ± 0.00061	259 ± 8	276	242	185	198	167
2016	NE	L	S	*	0.82	121 ± 11	1.060 ± 0.161	-0.00178 ± 0.00049	243 ± 7	257	229	163	174	146
2014	WI	H	AP	*	0.74	141 ± 9	0.953 ± 0.137	-0.00206 ± 0.00042	217 ± 5a	228	206	102	116	93
2014	WI	H	S	*	0.71	142 ± 9	0.717 ± 0.135	-0.00132 ± 0.00041	190 ± 5b	200	179	77	94	66
2014	WI	L	AP	*	0.81	127 ± 7	0.799 ± 0.111	-0.00151 ± 0.00034	209 ± 5	219	199	139	154	129
2014	WI	L	S	*	0.76	134 ± 8	0.730 ± 0.117	-0.00137 ± 0.00036a	201 ± 5	211	192	119	136	109
2015	WI	H	AP	*	0.30	185 ± 8	0.366 ± 0.125	-0.00081 ± 0.00038	185 ± 8	202	168	0	32	-62
2015	WI	H	S	*	0.24	188 ± 8	0.335 ± 0.125	-0.00081 ± 0.00040	188 ± 8	205	172	0	33	-62
2015	WI	L	AP	*	0.80	122 ± 9	0.667 ± 0.136	-0.00082 ± 0.00042	242 ± 6a	254	231	268	288	255
2015	WI	L	S	*	0.77	126 ± 8	0.675 ± 0.117	-0.00115 ± 0.00036	209 ± 5b	219	199	174	195	163
2016	WI	H	AP	*	0.80	168 ± 8	0.889 ± 0.115	-0.00186 ± 0.00035	241 ± 5	251	232	107	119	98
2016	WI	H	S	*	0.77	171 ± 8	0.771 ± 0.113	-0.00155 ± 0.00035	249 ± 5	259	240	144	160	133
2016	WI	L	AP	*	0.56	121 ± 13	0.630 ± 0.190	-0.00101 ± 0.00058	162 ± 7	177	147	73	107	60
2016	WI	L	S	*	0.74	121 ± 7	0.709 ± 0.102	-0.00152 ± 0.00031	167 ± 4	175	159	79	91	87

Level of significance for the regression model. ns = not significant, * = $p \leq 0.10$

† Not significant model, intercept, and/or slope PMN_E was reported as the average PMN across all N rates used in the model.

‡ Quadratic coefficient non-significant (ns) then linear regression was used.

§ Grain N concentration was not taken at ND in 2015.

Table 13. Grain N concentration (GNC) response to N rate (0 to 315 kg N ha-1 in 45 kg N ha-1 increments) and timing (T - all 'at-planting (AP)' or 'split (S)' with 45 or 90 kg N ha-1 at planting and the remainder at V9±1 V-stage) at two productivity site (Prod. - high (H) and low (L) based on historical yield data) in eight states over a three year period. Predicted values of GNC were calculated at the economic optimum N rate (EONR) (± standard error) for each productivity site and timing. Lower and upper 95% confidence limits (U and L CLM) were calculated for around the EONR and GNC at the EONR (GNCE). Regression coefficients and GNCE were considered non-significant if followed by (ns) and significant when not noted. Within a productivity-state-year differences between N application timings were noted by letters (a and b) for regression coefficients and GNCE.

Year	State	Prod.	T	Model†	Adj. R^2	a	bx	cx^2‡	GNC_E	UCLM	LCLM	EONR	UCLM	LCLM
									---------- g kg^{-1} ----------			------ kg N ha^{-1} ------		
2014	IA	H	AP	*	0.85	8.90 ± 0.15	0.0107 ± 0.0008	ns	10.6 ± 0.1	10.8	10.4	160	186	148
2014	IA	H	S	*	0.84	8.84 ± 0.18	0.0155 ± 0.0027	-0.000020 ± 0.000008	10.8 ± 0.1	11.0	10.5	153	175	142
2014	IA	L	AP	*	0.88	8.93 ± 0.17	0.0209 ± 0.0025	-0.000034 ± 0.000008	11.4 ± 0.1	11.6	11.2	160	174	152
2014	IA	L	S	*	0.85	8.94 ± 0.19	0.0220 ± 0.0028	-0.000040 ± 0.000009	11.4 ± 0.1	11.6	11.1	155	169	146
2015	IA	H	AP	*	0.74	8.92 ± 0.24	0.0190 ± 0.0036	-0.000032 ± 0.000011	10.9 ± 0.2	11.2	10.6	130	154	119
2015	IA	H	S	*	0.73	8.88 ± 0.24	0.0234 ± 0.0035	-0.000050 ± 0.000011	10.8 ± 0.1	11.1	10.5	107	122	97
2015	IA	L	AP	*	0.76	8.13 ± 0.27	0.0223 ± 0.0041	-0.000036 ± 0.000012	10.8 ± 0.2b	11.2	10.5	165	188	153
2015	IA	L	S	*	0.87	8.27 ± 0.20	0.0227 ± 0.0030	-0.000036 ± 0.000009	11.3 ± 0.1a	11.5	11.0	187	201	178
2016	IA	H	AP	*	0.61	9.73 ± 0.30	0.0114 ± 0.0016	ns	10.8 ± 0.2b	11.2	10.4	90	128	77
2016	IA	H	S	*	0.74	9.36 ± 0.28	0.0180 ± 0.0041	-0.000024 ± 0.000013	11.9 ± 0.2a	12.3	11.6	190	222	177
2016	IA	L	AP	*	0.75	8.62 ± 0.29	0.0237 ± 0.0044	-0.000039 ± 0.000013	11.7 ± 0.2	12.0	11.3	186	209	175
2016	IA	L	S	*	0.83	8.65 ± 0.24	0.0245 ± 0.0036	-0.000042 ± 0.000011	11.8 ± 0.1	12.1	11.5	188	205	179
2014	IL	H	AP	*	0.78	8.68 ± 0.24	0.0132 ± 0.0013a	ns	11.7 ± 0.2	12.0	11.4	226	269	269
2014	IL	H	S	*	0.78	8.83 ± 0.19	0.0104 ± 0.0010b	ns	11.6 ± 0.1	11.9	11.3	263	303	249
2014	IL	L	AP	*	0.60	9.28 ± 0.26	0.0097 ± 0.0014	ns	12.3 ± 0.3a	12.8	11.7	307	.	.
2014	IL	L	S	*	0.60	9.68 ± 0.24	0.0086 ± 0.0013	ns	11.7 ± 0.2b	12.1	11.4	237	.	.
2015	IL	H	AP	*	0.78	9.39 ± 0.18	0.0100 ± 0.0010	ns	11.9 ± 0.1	12.2	11.6	252	314	314
2015	IL	H	S	*	0.75	9.43 ± 0.20	0.0104 ± 0.0011	ns	11.9 ± 0.1	12.2	11.6	238	292	225
2015	IL	L	AP	*	0.56	9.96 ± 0.22	0.0075 ± 0.0012	ns	11.0 ± 0.1	11.3	10.8	141	224	224
2015	IL	L	S	*	0.55	9.93 ± 0.22	0.0071 ± 0.0012	ns	10.8 ± 0.1	11.1	10.6	124	179	179
2016	IL	H	AP	*	0.84	9.24 ± 0.15	0.0102 ± 0.0008b	ns	11.3 ± 0.1	11.5	11.1	205	232	193
2016	IL	H	S	*	0.86	9.09 ± 0.16	0.0170 ± 0.0024a	-0.000026 ± 0.000007	11.3 ± 0.1	11.5	11.1	177	193	168
2016	IL	L	AP	*	0.69	9.34 ± 0.28	0.0197 ± 0.0041	-0.000034 ± 0.000013	12.1 ± 0.2	12.4	11.7	228	251	216
2016	IL	L	S	*	0.76	9.34 ± 0.28	0.0220 ± 0.0042	-0.000035 ± 0.000013	12.0 ± 0.2	12.4	11.6	164	189	152

Table 13. Continued.

Year	State	Prod.	T	Model	Adj. R^2	a	bx	cx^2	GNC_E	UCLM	LCLM	EONR	UCLM	LCLM
									---------- g kg^{-1} ----------			------ kg N ha^{-1} ------		
2014	IN	H	AP	*	0.90	8.78 ± 0.23	0.0234 ± 0.0035	-0.000025 ± 0.000011	11.9 ± 0.1b	12.2	11.6	159	176	148
2014	IN	H	S	*	0.88	8.83 ± 0.25	0.0261 ± 0.0038	-0.000035 ± 0.000012	12.3 ± 0.2a	12.6	12.0	172	189	162
2014	IN	L	AP	*	0.76	9.43 ± 0.36	0.0269 ± 0.0054	-0.000040 ± 0.000016	13.1 ± 0.2	13.5	12.6	211	214	176
2014	IN	L	S	*	0.81	9.44 ± 0.33	0.0255 ± 0.0050	-0.000031 ± 0.000015	13.2 ± 0.2	13.6	12.8	215	217	180
2015	IN	H	AP	*	0.74	8.92 ± 0.26	0.0131 ± 0.0014b	ns	10.3 ± 0.2b	10.7	10.0	108	155	95
2015	IN	H	S	*	0.86	8.52 ± 0.24	0.0277 ± 0.0036a	-0.000047 ± 0.000011	11.8 ± 0.2a	12.1	11.4	160	174	151
2015	IN	L	AP	*	0.86	8.33 ± 0.28	0.0292 ± 0.0042	-0.000044 ± 0.000013	12.6 ± 0.2a	13.0	12.3	222	237	213
2015	IN	L	S	*	0.83	8.49 ± 0.28	0.0236 ± 0.0042	-0.000030 ± 0.000013	12.1 ± 0.2b	12.4	11.8	206	227	196
2016	IN	H	AP	*	0.67	8.08 ± 0.41	0.0365 ± 0.0061a	-0.000079 ± 0.000019	11.9 ± 0.3a	12.4	11.4	162	182	151
2016	IN	H	S	*	0.64	8.58 ± 0.35	0.0138 ± 0.0019b	ns	10.7 ± 0.2b	11.1	10.3	151	224	224
2016	IN	L	AP	*	0.88	9.76 ± 0.18	0.0197 ± 0.0026b	-0.000029 ± 0.000008a	11.9 ± 0.1b	12.1	11.6	132	146	123
2016	IN	L	S	*	0.78	9.74 ± 0.24	0.0288 ± 0.0036a	-0.000065 ± 0.000011b	12.3 ± 0.1a	12.6	12.0	119	132	111
2014	MN	H	AP	*	0.60	9.83 ± 0.24	0.0078 ± 0.0013	ns	11.2 ± 0.1	11.5	10.9	176	269	269
2014	MN	H	S	*	0.48	9.93 ± 0.24	0.0062 ± 0.0013	ns	10.9 ± 0.1	11.2	10.6	158	269	269
2014	MN	L	AP	*	0.69	9.50 ± 0.27	0.0120 ± 0.0014	ns	11.3 ± 0.1	11.6	11.0	147	224	224
2014	MN	L	S	*	0.67	9.46 ± 0.28	0.0184 ± 0.0043	-0.000031 ± 0.000013	11.2 ± 0.2	11.6	10.8	117	148	105
2015	MN	H	AP	*	0.61	9.94 ± 0.28	0.0197 ± 0.0042	-0.000039 ± 0.000013	11.5 ± 0.2b	11.8	11.2	99	122	87
2015	MN	H	S	*	0.44	10.06 ± 0.31	0.0211 ± 0.0046	-0.000053 ± 0.000014	12.0 ± 0.2a	12.4	11.6	151	181	138
2015	MN	L	AP	*	0.50	11.21 ± 0.23	0.0070 ± 0.0012	ns	12.6 ± 0.1	12.9	12.3	197	304	182
2015	MN	L	S	*	0.31	10.97 ± 0.31	0.0124 ± 0.0046	-0.000025 ± 0.000014	12.3 ± 0.2	12.7	11.9	166	273	150
2016	MN	H	AP	ns	0.04	8.88 ± 0.32	0.0026 ± 0.0017ans	ns	9.3 ± 0.2b	10.0	9.0	240	.	.
2016	MN	H	S	*	0.73	8.48 ± 0.27	0.0133 ± 0.0014b	ns	12.3 ± 0.2a	12.7	11.8	285	.	.
2016	MN	L	AP	*	0.71	9.15 ± 0.21	0.0097 ± 0.0011	ns	11.4 ± 0.1a	11.7	11.1	234	295	222
2016	MN	L	S	*	0.63	9.05 ± 0.27	0.0149 ± 0.0040	-0.000023 ± 0.000012	10.9 ± 0.2b	11.2	10.6	167	211	153

Table 13. Continued.

Year	State	Prod.	T	Model	Adj. R^2	a	bx	cx^2	GNC_E	UCLM	LCLM	EONR	UCLM	LCLM
									---------- g kg^{-1} ----------			------ kg N ha^{-1} ------		
2014	MO	H	AP	*	0.84	9.89 ± 0.22	0.0151 ± 0.0012	ns	13.3 ± 0.2a	13.6	13.0	224	259	211
2014	MO	H	S	*	0.81	10.08 ± 0.22	0.0134 ± 0.0012	ns	12.6 ± 0.1b	12.8	12.3	188	216	175
2014	MO	L	AP	*	0.72	9.90 ± 0.36	0.0162 ± 0.0019	ns	13.8 ± 0.2a	14.3	13.3	241	282	228
2014	MO	L	S	*	0.60	10.16 ± 0.38	0.0132 ± 0.0020	ns	12.5 ± 0.2b	12.9	12.1	177	231	163
2015	MO	H	AP	*	0.56	8.98 ± 0.30	0.0103 ± 0.0016	ns	11.8 ± 0.2	12.3	11.3	272	.	.
2015	MO	H	S	*	0.63	8.92 ± 0.25	0.0095 ± 0.0013	ns	11.9 ± 0.2	12.4	11.4	314	.	.
2015	MO	L	AP	ns	0.05	9.73 ± 0.33	-0.0029 ± 0.0018bns	ns	9.3 ± 0.1b	9.5	8.2	314	45	45
2015	MO	L	S	*	0.19	8.96 ± 0.45	0.0068 ± 0.0024a	ns	11.1 ± 0.4a	12.0	10.2	314	.	.
2016	MO	HA	AP	*	0.82	9.02 ± 0.27	0.0221 ± 0.0040b	-0.000029 ± 0.000012a	12.6 ± 0.2	13.0	12.3	239	258	229
2016	MO	HA	S	*	0.80	9.00 ± 0.28	0.0330 ± 0.0042a	-0.000068 ± 0.000013b	12.9 ± 0.2	13.3	12.6	205	218	196
2016	MO	HB	AP	*	0.87	8.68 ± 0.25	0.0227 ± 0.0038	-0.000026 ± 0.000012	12.8 ± 0.1a	13.1	12.5	258	273	247
2016	MO	HB	S	*	0.93	8.55 ± 0.18	0.0261 ± 0.0027	-0.000038 ± 0.000008	12.3 ± 0.1b	12.5	12.1	207	217	200
2016	MO	L	AP	*	0.88	7.99 ± 0.27	0.0328 ± 0.0041	-0.000053 ± 0.000012	11.9 ± 0.2b	12.3	11.6	164	177	155
2016	MO	L	S	*	0.86	8.11 ± 0.29	0.0356 ± 0.0044	-0.000063 ± 0.000013	12.6 ± 0.2a	13.0	12.2	191	204	183
2014	ND	H	AP	*	0.62	11.02 ± 0.25	0.0094 ± 0.0013	ns	12.6 ± 0.1	12.9	12.4	171	219	157
2014	ND	H	S	*	0.65	10.89 ± 0.27	0.0110 ± 0.0014	ns	12.7 ± 0.1	13.0	12.4	164	224	224
2014	ND	L	AP	*	0.28	10.97 ± 0.58	0.0112 ± 0.0031	ns	13.0 ± 0.3	13.6	12.3	177	269	269
2014	ND	L	S	*	0.49	11.28 ± 0.45	0.0134 ± 0.0024	ns	13.5 ± 0.2	14.0	13.0	165	224	224
2015	ND	H	AP	§	.	.	.	.	.	.	.	192	.	.
2015	ND	H	S	.	.	.	.	.	.	.	.	155	.	.
2015	ND	L	AP	.	.	.	.	.	.	.	.	101	.	.
2015	ND	L	S	.	.	.	.	.	.	.	.	139	.	.
2016	ND	H	AP	*	0.14	11.94 ± 0.17	0.0023 ± 0.0009	ns	11.9 ± 0.2	12.3	11.6	45	52	-55
2016	ND	H	S	*	0.18	12.05 ± 0.21	0.0031 ± 0.0011	ns	12.0 ± 0.2	12.5	11.6	45	40	-72
2016	ND	L	AP	ns	0.00	14.04 ± 0.49	0.0026 ± 0.0026ns	ns	14.4 ± 0.1	15.0	13.0	0	224	224
2016	ND	L	S	*	0.12	14.00 ± 0.48	0.0058 ± 0.0026	ns	14.0 ± 0.5	15.0	13.0	0	179	179

Table 13. Continued.

Year	State	Prod.	T	Model	Adj. R^2	a	bx	cx^2	GNC_E	UCLM	LCLM	EONR	UCLM	LCLM
									---------- g kg^{-1} ----------			------ kg N ha^{-1} ------		
2014	NE	H	AP	*	0.32	11.98 ± 0.23	0.0049 ± 0.0012	ns	12.4 ± 0.1b	12.7	12.1	114	179	179
2014	NE	H	S	*	0.34	12.03 ± 0.25	0.0055 ± 0.0014	ns	12.8 ± 0.1a	13.1	12.5	157	224	224
2014	NE	L	AP	*	0.23	10.53 ± 0.26	0.0045 ± 0.0014	ns	11.8 ± 0.2	12.3	11.3	307	.	.
2014	NE	L	S	*	0.33	11.00 ± 0.28	0.0060 ± 0.0015	ns	12.2 ± 0.2	12.6	11.9	217	.	.
2015	NE	H	AP	*	0.27	12.60 ± 0.25	0.0047 ± 0.0013	ns	12.7 ± 0.2	13.2	12.3	46	134	134
2015	NE	H	S	*	0.19	12.81 ± 0.18	0.0028 ± 0.0010	ns	12.9 ± 0.2	13.2	12.6	46	64	2
2015	NE	L	AP	*	0.27	10.46 ± 0.18	-0.0033 ± 0.0009b	ns	9.4 ± 0.2b	9.8	9.1	314	0	0
2015	NE	L	S	*	0.45	10.03 ± 0.26	0.0071 ± 0.0014a	ns	11.4 ± 0.2a	11.7	11.1	210	269	269
2016	NE	H	AP	*	0.41	8.76 ± 0.33	0.0193 ± 0.0050	-0.000045 ± 0.000015	9.4 ± 0.2	9.9	9.0	56	58	17
2016	NE	H	S	*	0.44	8.57 ± 0.33	0.0199 ± 0.0049	-0.000046 ± 0.000015	9.2 ± 0.2	9.7	8.8	56	57	17
2016	NE	L	AP	*	0.80	6.43 ± 0.30	0.0362 ± 0.0045	-0.000077 ± 0.000014	10.4 ± 0.2a	10.8	10.0	185	191	169
2016	NE	L	S	*	0.84	6.20 ± 0.29	0.0339 ± 0.0044	-0.000062 ± 0.000013	10.0 ± 0.2b	10.4	9.6	163	171	147
2014	WI	H	AP	*	0.83	10.15 ± 0.16	0.0146 ± 0.0024	-0.000021 ± 0.000007	11.4 ± 0.1a	11.6	11.2	102	118	92
2014	WI	H	S	*	0.86	10.20 ± 0.15	0.0133 ± 0.0022	-0.000017 ± 0.000007	11.1 ± 0.1b	11.3	11.0	77	91	67
2014	WI	L	AP	*	0.90	9.96 ± 0.18	0.0189 ± 0.0028	-0.000021 ± 0.000008	12.2 ± 0.1	12.4	11.9	139	155	129
2014	WI	L	S	*	0.92	10.19 ± 0.15	0.0173 ± 0.0022	-0.000020 ± 0.000007	12.0 ± 0.1	12.2	11.8	119	132	110
2015	WI	H	AP	*	0.64	12.12 ± 0.13	0.0054 ± 0.0007	ns	12.1 ± 0.1	12.4	11.9	0	33	-64
2015	WI	H	S	*	0.53	11.97 ± 0.19	0.0105 ± 0.0030	-0.000020 ± 0.000010	12.0 ± 0.2	12.4	11.6	0	26	-49
2015	WI	L	AP	*	0.81	9.95 ± 0.26	0.0247 ± 0.0038	-0.000041 ± 0.000012	13.6 ± 0.2a	13.9	13.3	268	282	257
2015	WI	L	S	*	0.85	10.04 ± 0.21	0.0215 ± 0.0031	-0.000033 ± 0.000010	12.8 ± 0.1b	13.0	12.5	174	191	164
2016	WI	H	AP	*	0.83	10.88 ± 0.22	0.0257 ± 0.0033	-0.000048 ± 0.000010	13.1 ± 0.1	13.3	12.8	107	119	98
2016	WI	H	S	*	0.75	10.96 ± 0.22	0.0210 ± 0.0032	-0.000042 ± 0.000010	13.1 ± 0.1	13.4	12.8	144	161	133
2016	WI	L	AP	*	0.82	10.65 ± 0.26	0.0262 ± 0.0039	-0.000045 ± 0.000012	12.3 ± 0.1	12.6	12.0	73	86	63
2016	WI	L	S	*	0.76	10.60 ± 0.31	0.0303 ± 0.0046	-0.000060 ± 0.000014	12.6 ± 0.2	13.0	12.3	79	92	69

Level of significance for the regression model. ns = not significant, * = $p \leq 0.10$

† Not significant model, intercept, and/or slope GNC_E was reported as the average GNC across all N rates used in the model.

‡ Quadratic coefficient non-significant (ns) then linear regression was used.

§ Grain N concentration was not taken at ND in 2015.

Table 14. Stover N concentration at maturity (SNC) response to N rate (0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) and timing (T - all 'at-planting (AP)' or 'split (S)' with 45 or 90 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) at two productivity site (Prod. - low (L) and high (H) based on historical yield data) in eight states over a three year period (2014, 2015, and 2016). Predicted values of SNC were calculated at the economic optimum N rate (EONR) (± standard error) for each productivity site and timing. Lower and upper 95% confidence limits (U and L CLM) were calculated for around the EONR and SNC at the EONR (SNC_E). Regression coefficients and SNC_E were considered non-significant if followed by (ns) and significant when not noted. Within a productivity-state-year differences between N application timings were noted by letters (a and b) for regression coefficients and SNC_E.

Year	State	Prod.	T	Model†	Adj. R^2	a	bx	cx^2‡	SNC_E	UCLM	LCLM	EONR	UCLM	LCLM
									---------- g kg^{-1} ----------			------- kg N ha^{-1} -------		
2014	IA	H	AP	*	0.44	7.11 ± 0.38	0.010 ± 0.002	ns	8.7 ± 0.2	9.2	8.3	160	224	224
2014	IA	H	S	*	0.66	7.17 ± 0.25	0.011 ± 0.001	ns	8.8 ± 0.1	9.1	8.5	153	224	224
2014	IA	L	AP	*	0.62	5.95 ± 0.45	0.029 ± 0.007a	-0.000054 ± 0.000021	9.3 ± 0.3a	9.9	8.7	160	194	147
2014	IA	L	S	*	0.64	6.44 ± 0.35	0.014 ± 0.002b	ns	8.6 ± 0.2b	9.0	8.2	155	224	224
2015	IA	H	AP	*	0.81	6.42 ± 0.28	0.017 ± 0.001b	ns	8.6 ± 0.2b	8.9	8.3	130	179	179
2015	IA	H	S	*	0.66	6.29 ± 0.47	0.037 ± 0.007a	-0.000077 ± 0.000021	9.4 ± 0.3a	10.0	8.8	107	127	95
2015	IA	L	AP	*	0.83	5.15 ± 0.25	0.016 ± 0.001	ns	7.8 ± 0.1b	8.1	7.6	165	224	224
2015	IA	L	S	*	0.81	5.60 ± 0.28	0.017 ± 0.001	ns	8.8 ± 0.2a	9.1	8.5	187	222	174
2016	IA	H	AP	*	0.68	5.71 ± 0.68	0.040 ± 0.010	-0.000056 ± 0.000031	8.8 ± 0.4b	9.6	8.0	90	119	77
2016	IA	H	S	*	0.58	5.79 ± 0.63	0.032 ± 0.009	-0.000050 ± 0.000029	10.1 ± 0.4a	10.9	9.3	190	241	175
2016	IA	L	AP	*	0.77	5.41 ± 0.31	0.017 ± 0.002	ns	8.6 ± 0.2	8.9	8.2	186	224	224
2016	IA	L	S	*	0.72	5.31 ± 0.39	0.024 ± 0.006	-0.000031 ± 0.000018	8.7 ± 0.2	9.2	8.2	188	225	223
2014	IL	H	AP	*	0.44	4.22 ± 0.32	0.009 ± 0.002	ns	6.2 ± 0.2	6.6	5.7	226	314	314
2014	IL	H	S	*	0.55	4.16 ± 0.24	0.008 ± 0.001	ns	6.3 ± 0.2	6.7	5.9	263	.	.
2014	IL	L	AP	*	0.60	3.71 ± 0.31	0.012 ± 0.002	ns	7.3 ± 0.3	7.9	6.7	307	.	.
2014	IL	L	S	*	0.64	3.99 ± 0.29	0.012 ± 0.002	ns	6.7 ± 0.2	7.1	6.3	237	304	225
2015	IL	H	AP	*	0.43	4.79 ± 0.27	0.007 ± 0.001	ns	6.6 ± 0.2	7.0	6.2	252	.	.
2015	IL	H	S	*	0.51	4.88 ± 0.25	0.008 ± 0.001	ns	6.7 ± 0.2	7.1	6.4	238	314	314
2015	IL	L	AP	*	0.54	4.30 ± 0.24	0.008 ± 0.001	ns	5.4 ± 0.1	5.7	5.1	141	20	131
2015	IL	L	S	*	0.49	4.28 ± 0.28	0.008 ± 0.001	ns	5.3 ± 0.2	5.6	5.0	124	179	179
2016	IL	H	AP	*	0.66	5.41 ± 0.27	0.011 ± 0.001a	ns	7.7 ± 0.2a	8.1	7.4	205	269	269
2016	IL	H	S	*	0.68	5.57 ± 0.19	0.008 ± 0.001b	ns	7.0 ± 0.1b	7.3	6.8	177	224	224
2016	IL	L	AP	*	0.70	5.41 ± 0.34	0.016 ± 0.002b	ns	9.0 ± 0.2	9.4	8.5	228	269	269
2016	IL	L	S	*	0.73	5.06 ± 0.46	0.031 ± 0.007a	-0.000046 ± 0.000021	9.0 ± 0.3	9.6	8.4	164	194	151

Table 14. Continued.

Year	State	Prod.	T	Model	Adj. R^2	a	bx	cx^2	SNC_E	UCLM	LCLM	EONR	UCLM	LCLM
									---------- g kg^{-1} ----------			------- kg N ha^{-1} -------		
2014	IN	H	AP	*	0.83	5.29 ± 0.20	0.013 ± 0.001	ns	7.4 ± 0.1	7.6	7.1	159	187	146
2014	IN	H	S	*	0.82	5.27 ± 0.19	0.012 ± 0.001	ns	7.3 ± 0.1	7.5	7.1	172	210	158
2014	IN	L	AP	*	0.73	5.41 ± 0.33	0.016 ± 0.002	ns	8.4 ± 0.2	8.8	8.1	211	224	224
2014	IN	L	S	*	0.90	5.29 ± 0.19	0.017 ± 0.001	ns	8.5 ± 0.1	8.7	8.3	215	224	224
2015	IN	H	AP	*	0.71	4.04 ± 0.62	0.029 ± 0.003	ns	7.2 ± 0.4b	7.9	6.4	108	179	179
2015	IN	H	S	*	0.85	4.57 ± 0.46	0.033 ± 0.002	ns	9.8 ± 0.3a	10.3	9.3	160	223	145
2015	IN	L	AP	*	0.82	4.54 ± 0.28	0.018 ± 0.002	ns	8.6 ± 0.2a	8.9	8.2	222	261	209
2015	IN	L	S	*	0.76	4.59 ± 0.32	0.017 ± 0.002	ns	8.1 ± 0.2b	8.4	7.7	206	269	269
2016	IN	H	AP	*	0.82	4.57 ± 0.32	0.020 ± 0.002	ns	7.8 ± 0.2	8.2	7.5	162	224	224
2016	IN	H	S	*	0.79	4.75 ± 0.30	0.022 ± 0.005	-0.000027 ± 0.000014	7.4 ± 0.2	7.8	7.0	151	180	178
2016	IN	L	AP	*	0.82	6.39 ± 0.26	0.017 ± 0.001b	ns	8.6 ± 0.1b	8.9	8.3	132	164	119
2016	IN	L	S	*	0.85	6.12 ± 0.27	0.031 ± 0.004a	-0.000054 ± 0.000012	9.0 ± 0.2a	9.3	8.7	119	133	110
2014	MN	H	AP	*	0.52	6.58 ± 0.31	0.008 ± 0.002a	ns	8.0 ± 0.2a	8.4	7.7	176	269	269
2014	MN	H	S	*	0.25	6.87 ± 0.29	0.004 ± 0.002b	ns	7.6 ± 0.2b	7.9	7.2	158	.	.
2014	MN	L	AP	*	0.74	6.40 ± 0.23	0.012 ± 0.001	ns	8.1 ± 0.1	8.4	7.9	147	189	133
2014	MN	L	S	*	0.79	6.44 ± 0.21	0.012 ± 0.001	ns	7.9 ± 0.1	8.2	7.6	117	170	103
2015	MN	H	AP	*	0.65	6.49 ± 0.20	0.011 ± 0.003	-0.000016 ± 0.000009	7.5 ± 0.1b	7.7	7.2	99	132	86
2015	MN	H	S	*	0.54	6.43 ± 0.27	0.015 ± 0.004	-0.000027 ± 0.000012	8.1 ± 0.2a	8.4	7.7	151	197	136
2015	MN	L	AP	*	0.64	7.91 ± 0.31	0.012 ± 0.002	ns	10.3 ± 0.2	10.7	9.9	197	257	182
2015	MN	L	S	*	0.64	7.43 ± 0.38	0.021 ± 0.006	-0.000030 ± 0.000018	10.1 ± 0.2	10.6	9.6	166	213	152
2016	MN	H	AP	ns	-0.03	4.95 ± 0.20	0.000 ± 0.001bns	ns	5.0 ± 0.1b	5.3	4.7	240	.	.
2016	MN	H	S	*	0.69	4.65 ± 0.22	0.010 ± 0.001a	ns	7.5 ± 0.2a	7.9	7.1	285	.	.
2016	MN	L	AP	*	0.69	5.35 ± 0.22	0.010 ± 0.001	ns	7.7 ± 0.2a	8.0	7.3	234	303	222
2016	MN	L	S	*	0.77	5.45 ± 0.20	0.011 ± 0.001	ns	7.3 ± 0.1b	7.5	7.1	167	202	154

Table 14. Continued.

Year	State	Prod.	T	Model	Adj. R^2	a	bx	cx^2	SNC_E	UCLM	LCLM	EONR	UCLM	LCLM
									---------- g kg^{-1} ----------			------- kg N ha^{-1} -------		
2014	MO	H	AP	*	0.57	6.05 ± 0.71	0.036 ± 0.010	-0.000061 ± 0.000031	11.1 ± 0.4	11.9	10.4	224	263	212
2014	MO	H	S	*	0.54	5.84 ± 0.77	0.041 ± 0.011	-0.000075 ± 0.000033	10.9 ± 0.4	11.8	10.0	188	230	174
2014	MO	L	AP	*	0.63	5.42 ± 0.36	0.014 ± 0.002	ns	8.8 ± 0.3a	9.3	8.3	241	314	314
2014	MO	L	S	*	0.67	5.73 ± 0.33	0.014 ± 0.002	ns	8.2 ± 0.2b	8.5	7.8	177	224	224
2015	MO	H	AP	*	0.48	4.71 ± 0.51	0.015 ± 0.003a	ns	8.8 ± 0.4a	9.7	7.9	272	.	.
2015	MO	H	S	*	0.15	4.94 ± 0.49	0.007 ± 0.003b	ns	7.0 ± 0.5b	8.0	6.0	314	.	.
2015	MO	L	AP	*	0.42	8.89 ± 0.47	-0.029 ± 0.007	0.000069 ± 0.000021	6.7 ± 0.5b	7.6	5.7	314	.	.
2015	MO	L	S	*	0.49	8.96 ± 0.52	-0.032 ± 0.008	0.000119 ± 0.000024	10.6 ± 0.5a	11.7	9.6	314	.	.
2016	MO	HA	AP	*	0.77	8.06 ± 0.50	0.027 ± 0.003b	ns	14.6 ± 0.4	15.3	13.9	239	286	227
2016	MO	HA	S	*	0.70	7.81 ± 0.62	0.050 ± 0.009a	-0.000094 ± 0.000028	14.1 ± 0.4	14.8	13.3	205	227	194
2016	MO	HB	AP	*	0.79	5.89 ± 0.44	0.025 ± 0.002	ns	12.3 ± 0.3a	13.0	11.7	258	314	314
2016	MO	HB	S	*	0.82	6.18 ± 0.36	0.023 ± 0.002	ns	11.0 ± 0.2b	11.5	10.6	207	269	269
2016	MO	L	AP	*	0.85	7.23 ± 0.40	0.028 ± 0.002	ns	11.8 ± 0.2	12.3	11.4	164	189	152
2016	MO	L	S	*	0.84	7.43 ± 0.35	0.024 ± 0.002	ns	12.0 ± 0.2	12.4	11.6	191	223	179
2014	ND	H	AP	*	0.29	5.36 ± 0.46	0.009 ± 0.002	ns	6.9 ± 0.3	7.4	6.4	171	269	269
2014	ND	H	S	ns	-0.01	6.14 ± 0.58	0.003 ± 0.003ns	ns	6.5 ± 0.4	7.2	5.9	164	.	.
2014	ND	L	AP	*	0.36	6.33 ± 0.60	-0.015 ± 0.009b	0.000075 ± 0.000027	6.0 ± 0.4b	6.8	5.2	177	8	163
2014	ND	L	S	*	0.22	5.90 ± 0.61	0.010 ± 0.003a	ns	7.6 ± 0.3a	8.3	6.9	165	269	269
2015	ND	H	AP	*	0.20	6.96 ± 0.45	0.007 ± 0.002	ns	8.4 ± 0.3	8.9	7.8	192	.	.
2015	ND	H	S	*	0.19	6.86 ± 0.50	0.008 ± 0.003	ns	8.1 ± 0.3	8.6	7.5	155	.	.
2015	ND	L	AP	*	0.33	7.21 ± 0.39	0.008 ± 0.002	ns	8.0 ± 0.2	8.5	7.6	101	179	179
2015	ND	L	S	*	0.42	7.02 ± 0.40	0.010 ± 0.002	ns	8.5 ± 0.2	8.9	8.0	139	224	224
2016	ND	H	AP	*	0.26	6.32 ± 0.28	0.005 ± 0.002	ns	6.3 ± 0.3	6.9	5.7	45	224	224
2016	ND	H	S	*	0.12	6.57 ± 0.28	0.003 ± 0.002	ns	6.6 ± 0.3	7.2	6.0	45	179	179
2016	ND	L	AP	ns	-0.03	6.32 ± 0.66	0.000 ± 0.004ns	ns	6.4 ± 0.3	7.7	5.0	0	.	.
2016	ND	L	S	*	0.16	6.06 ± 0.49	0.007 ± 0.003	ns	6.1 ± 0.5	7.1	5.1	0	179	179

Table 14. Continued.

Year	State	Prod.	T	Model	Adj. R^2	a	bx	cx^2	SNC_E	UCLM	LCLM	EONR	UCLM	LCLM
									---------- g kg^{-1} ----------			------- kg N ha^{-1} -------		
2014	NE	H	AP	*	0.39	8.87 ± 0.40	0.010 ± 0.002	ns	9.8 ± 0.3b	10.3	9.3	114	179	179
2014	NE	H	S	*	0.25	9.52 ± 0.39	0.007 ± 0.002	ns	10.5 ± 0.2a	11.0	10.1	157	.	.
2014	NE	L	AP	*	0.19	7.16 ± 0.41	0.006 ± 0.002b	ns	9.0 ± 0.4	9.8	8.2	307	.	.
2014	NE	L	S	*	0.52	7.18 ± 0.39	0.012 ± 0.002a	ns	9.7 ± 0.2	10.2	9.2	217	269	269
2015	NE	H	AP	*	0.16	10.21 ± 0.48	0.007 ± 0.003	ns	10.4 ± 0.4	11.3	9.5	46	134	134
2015	NE	H	S	*	0.26	10.08 ± 0.45	0.008 ± 0.002	ns	10.3 ± 0.4	11.1	9.5	46	134	134
2015	NE	L	AP	ns	-0.03	7.79 ± 0.26	0.000 ± 0.001bns	ns	7.8 ± 0.1b	8.4	7.4	314	.	.
2015	NE	L	S	*	0.43	7.58 ± 0.39	0.010 ± 0.002a	ns	9.7 ± 0.2a	10.1	9.2	210	.	.
2016	NE	H	AP	*	0.19	10.12 ± 0.49	0.019 ± 0.007a	-0.000049 ± 0.000022	10.8 ± 0.3	11.4	10.1	56	69	16
2016	NE	H	S	*	0.15	10.61 ± 0.46	0.006 ± 0.002b	ns	10.8 ± 0.4	11.6	10.0	56	134	134
2016	NE	L	AP	*	0.27	8.91 ± 0.54	0.010 ± 0.003	ns	10.7 ± 0.3	11.4	10.1	185	269	269
2016	NE	L	S	*	0.34	8.72 ± 0.50	0.011 ± 0.003	ns	10.4 ± 0.3	11.0	9.9	163	269	269
2014	WI	H	AP	*	0.28	7.97 ± 0.42	0.008 ± 0.002	ns	8.8 ± 0.3	9.3	8.2	102	179	179
2014	WI	H	S	*	0.39	7.62 ± 0.40	0.010 ± 0.002	ns	8.4 ± 0.3	8.9	7.8	77	179	179
2014	WI	L	AP	*	0.42	6.55 ± 0.45	0.021 ± 0.007	-0.000039 ± 0.000021	8.7 ± 0.3	9.2	8.1	139	207	124
2014	WI	L	S	*	0.55	6.66 ± 0.37	0.023 ± 0.006	-0.000046 ± 0.000017	8.8 ± 0.2	9.2	8.3	119	151	106
2015	WI	H	AP	*	0.12	9.65 ± 0.53	0.007 ± 0.003	ns	9.6 ± 0.5	10.7	8.6	0	45	-71
2015	WI	H	S	*	0.12	9.85 ± 0.40	0.005 ± 0.002	ns	9.9 ± 0.4	10.7	9.0	0	56	-37
2015	WI	L	AP	*	0.58	7.27 ± 0.37	0.013 ± 0.002	ns	10.8 ± 0.3a	11.4	10.2	268	.	.
2015	WI	L	S	*	0.53	7.46 ± 0.30	0.010 ± 0.002	ns	9.1 ± 0.2b	9.5	8.8	174	224	224
2016	WI	H	AP	*	0.88	6.42 ± 0.43	0.045 ± 0.006a	-0.000061 ± 0.000020	10.5 ± 0.3	11.0	9.9	107	121	97
2016	WI	H	S	*	0.63	6.85 ± 0.43	0.029 ± 0.006b	-0.000052 ± 0.000020	9.9 ± 0.3	10.4	9.3	144	175	130
2016	WI	L	AP	*	0.68	5.55 ± 0.70	0.030 ± 0.004a	ns	7.8 ± 0.5	8.8	6.8	73	134	134
2016	WI	L	S	*	0.56	6.50 ± 0.50	0.017 ± 0.003b	ns	7.8 ± 0.3	8.6	7.1	79	117	66

Level of significant for the regression model. ns = not significant; * = $p \leq 0.10$

† Not significant model, intercept, and/or slope SNC_E was reported as the average SNC across all N rates used in the model.

‡ Quadratic coefficient non-significant (ns) then linear regression was used.

Table 15. Stover dry matter (SDM) response to N rate (0 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) and timing (T - all 'at-planting (AP)' or 'split (S)' with 45 or 90 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) at two productivity site (Prod. - high (H) and low (L) based on historical data) in eight states over a three year period (2014, 2015, and 2016). Site-years and N application timings were test for a linear, quadratic, and quadratic-plateau (L, Q, and QP, respectively) models. Predicted values of SDM were calculated at the economic optimum N rate (EONR) and plateau N rate (± standard error) for each productivity site and timing. Upper and lower 95% confidence limits (U and L CLM) were calculated around the EONR and SDM at the EONR (SDM_E). For QP models, the plateau N rate is noted under the UCLM. Regression coefficients and SDM_E were considered non-significant if followed by (ns) and significant when not noted.

Year	State	Prod.	T	Model†	Adj. R^2	a	bx	cx^2‡	SDM_E	SDM Plateau	UCLM	LCLM	EONR	UCLM	LCLM
									---------------- kg DM ha^{-1} ----------------				---- kg N ha^{-1} ----		
2014	IA	H	AP	QP	0.89	4231 ± 263	53.48 ± 7.16	-0.1600 ± 0.0379	8693 ± 121a	8700 ± 135a	.	8445	160	167	121
2014	IA	H	S	QP	0.80	4290 ± 295	48.86 ± 9.47	-0.1682 ± 0.0579	7839 ± 142b	7839 ± 142b	.	7548	153	145	94
2014	IA	L	AP	QP	0.72	7705 ± 271	21.60 ± 4.54	-0.0399 ± 0.0153	10143 ± 175a	10626 ± 208a	10501	9786	160	270	125
2014	IA	L	S	Q	0.32	7922 ± 312	14.03 ± 4.66	-0.0304 ± 0.0143	9363 ± 200b	.	9772	8955	155	229	139
2015	IA	H	AP	Q	0.43	6204 ± 483	23.55 ± 7.21	-0.0461 ± 0.0221	8492 ± 302	.	9110	7875	130	186	116
2015	IA	H	S	Q	0.34	6049 ± 508	31.56 ± 7.58	-0.0969 ± 0.0232	8312 ± 302	.	8929	7696	107	136	94
2015	IA	L	AP	QP	0.79	5544 ± 357	72.34 ± 14.48	-0.3105 ± 0.1114	9757 ± 160a	9757 ± 160a	.	9430	165	116	73
2015	IA	L	S	QP	0.72	5526 ± 330	85.61 ± 21.72	-0.5668 ± 0.2653	8759 ± 135b	8759 ± 135b	.	8484	187	76	40
2016	IA	H	AP	ns	-0.02	11322 ± 923	3.58 ± 4.92ns	ns	11883 ± 530	.	12877	10411	90	.	.
2016	IA	H	S	ns	0.03	10484 ± 613	4.44 ± 3.27ns	ns	11181 ± 331	.	12047	10608	190	.	.
2016	IA	L	AP	Q	0.39	8018 ± 350	19.20 ± 5.22a	-0.0438 ± 0.0160	10072 ± 218a	.	10518	9627	186	231	172
2016	IA	L	S	L	0.18	8535 ± 249	3.76 ± 1.33b	ns	9244 ± 143b	.	9535	8952	188	.	.
2014	IL	H	AP	QP	0.74	4659 ± 367	64.55 ± 14.93	-0.2778 ± 0.1152	8410 ± 164a	8410 ± 164a	.	8074	226	116	69
2014	IL	H	S	QP	0.71	4766 ± 313	52.11 ± 13.19	-0.2305 ± 0.1049	7712 ± 139b	7712 ± 139b	.	7427	263	113	64
2014	IL	L	AP	Q	0.46	3961 ± 573	29.85 ± 8.55	-0.0594 ± 0.0262	7528 ± 527	.	8607	6450	307	.	.
2014	IL	L	S	QP	0.68	3836 ± 408	37.72 ± 9.50	-0.0966 ± 0.0433	7519 ± 232	7519 ± 232	.	7044	237	195	22
2015	IL	H	AP	QP	0.67	5602 ± 193	20.21 ± 5.17	-0.0598 ± 0.0270	7311 ± 99a	7311 ± 99a	.	7107	252	169	79
2015	IL	H	S	Q	0.44	5764 ± 160	10.43 ± 2.39	-0.0253 ± 0.0073	6815 ± 91b	.	7001	6630	238	263	226
2015	IL	L	AP	ns	0.06	9355 ± 638	-5.61 ± 3.30ns	ns	8428 ± 551	.	9278	7852	141	.	.
2015	IL	L	S	L	0.23	9092 ± 595	-9.79 ± 3.12	ns	7879 ± 339	.	8573	7185	124	.	.
2016	IL	H	AP	Q	0.47	5833 ± 302	16.69 ± 4.62	-0.0349 ± 0.0144	7791 ± 185a	.	8170	7411	205	249	192
2016	IL	H	S	Q	0.40	5934 ± 238	13.52 ± 3.55	-0.0312 ± 0.0109	7350 ± 150b	.	7657	7044	177	220	163
2016	IL	L	AP	QP	0.59	4808 ± 292	17.50 ± 4.90	-0.0324 ± 0.0166	7111 ± 156a	7169 ± 222a	.	6793	228	270	152
2016	IL	L	S	L	0.12	5240 ± 197	2.56 ± 1.05b	ns	5659 ± 108b	.	5880	5438	164	.	.

Table 15. Continued.

Year	State	Prod.	T	Model†	Adj. R²	a	bx	cx²‡	SDM_E	SDM Plateau	UCLM	LCLM	EONR	UCLM	LCLM
									---------------- kg DM ha^{-1} ----------------				---- kg N ha^{-1} ----		
2014	IN	H	AP	Q	0.35	6933 ± 372	21.32 ± 5.55	-0.0540 ± 0.0170	8956 ± 238	.	9442	8470	159	201	144
2014	IN	H	S	Q	0.37	7022 ± 342	18.20 ± 5.11	-0.0421 ± 0.0156	8906 ± 217	.	9350	8461	172	221	157
2014	IN	L	AP	Q	0.22	8074 ± 262	9.81 ± 3.91	-0.0219 ± 0.0120	9145 ± 162	.	9477	8814	211	.	.
2014	IN	L	S	L	0.25	8440 ± 245	4.38 ± 1.31	ns	9280 ± 142	.	9570	8991	215	.	.
2015	IN	H	AP	L	0.06	6313 ± 287	2.60 ± 1.53b	ns	6594 ± 174b	.	6949	6240	108	.	.
2015	IN	H	S	L	0.41	6059 ± 246	6.19 ± 1.31a	ns	7049 ± 135a	.	7324	6774	160	269	269
2015	IN	L	AP	QP	0.78	5827 ± 280	35.33 ± 6.93	-0.0964 ± 0.0334	9063 ± 150	9063 ± 150	.	8756	222	183	119
2015	IN	L	S	QP	0.67	5848 ± 345	35.07 ± 8.95	-0.1003 ± 0.0451	8913 ± 180	8913 ± 180	.	8544	206	175	103
2016	IN	H	AP	QP	0.62	6172 ± 276	14.85 ± 4.10	-0.0218 ± 0.0125	8004 ± 176a	8691 ± 279	8363	7645	162	315	122
2016	IN	H	S	Q	0.45	6254 ± 241	10.87 ± 3.60	-0.0192 ± 0.0110	7459 ± 154b	.	7774	7144	151	225	223
2016	IN	L	AP	Q	0.40	6341 ± 284	13.11 ± 4.24	-0.0258 ± 0.0130	7622 ± 178	.	7986	7258	132	196	117
2016	IN	L	S	Q	0.19	6311 ± 425	19.12 ± 6.34	-0.0574 ± 0.0194	7776 ± 260	.	8307	7244	119	183	105
2014	MN	H	AP	QP	0.66	3241 ± 334	25.06 ± 7.49	-0.0620 ± 0.0330	5733 ± 159a	5773 ± 195	.	5403	176	202	109
2014	MN	H	S	Q	0.44	3449 ± 228	12.50 ± 3.40	-0.0295 ± 0.0104	4688 ± 146b	.	4991	4384	158	206	144
2014	MN	L	AP	QP	0.68	3820 ± 409	40.84 ± 11.64	-0.1241 ± 0.0627	7143 ± 172a	7180 ± 182a	.	6787	147	165	89
2014	MN	L	S	QP	0.72	3731 ± 277	59.13 ± 15.82	-0.3387 ± 0.1640	6311 ± 98b	6311 ± 98b	.	6110	117	87	46
2015	MN	H	AP	QP	0.75	4605 ± 361	59.13 ± 13.74	-0.2316 ± 0.0959	8184 ± 239	8379 ± 164	.	7693	99	128	67
2015	MN	H	S	Q	0.49	4994 ± 400	28.19 ± 5.97	-0.0675 ± 0.0183	7708 ± 256	.	8231	7186	151	180	178
2015	MN	L	AP	QP	0.78	6987 ± 230	23.13 ± 4.40	-0.0487 ± 0.0167	9655 ± 117a	9735 ± 154	.	9415	197	238	148
2015	MN	L	S	Q	0.42	7077 ± 284	16.52 ± 4.24	-0.0380 ± 0.0130	8772 ± 181b	.	9142	8401	166	207	152
2016	MN	H	AP	Q	0.49	3235 ± 531	27.37 ± 7.92a	-0.0508 ± 0.0243	6874 ± 300	.	7487	6262	240	278	227
2016	MN	H	S	L	0.43	3758 ± 478	12.17 ± 2.55b	ns	7221 ± 418	.	8074	6367	285	.	.
2016	MN	L	AP	QP	0.82	4767 ± 228	27.44 ± 4.53	-0.0606 ± 0.0178	7873 ± 143a	7873 ± 143a	.	7581	234	226	158
2016	MN	L	S	QP	0.67	4616 ± 242	41.49 ± 11.99	-0.2067 ± 0.1085	6698 ± 104b	6698 ± 104b	.	6485	167	100	53

Table 15. Continued.

Year	State	Prod.	T	Model†	Adj. R^2	a	bx	cx^2‡	SDM_E	SDM Plateau	UCLM	LCLM	EONR	UCLM	LCLM
									---------------- kg DM ha^{-1} ----------------				---- kg N ha^{-1} ----		
2014	MO	H	AP	L	0.47	8751 ± 402	11.47 ± 2.25	ns	11319 ± 282a	.	11897	10742	224	309	211
2014	MO	H	S	Q	0.20	8357 ± 516	18.47 ± 7.70	-0.0412 ± 0.0236	10371 ± 320b	.	11026	9717	188	.	.
2014	MO	L	AP	Q	0.25	9429 ± 596	23.33 ± 8.90	-0.0510 ± 0.0273	12087 ± 337	.	12776	11399	241	.	.
2014	MO	L	S	Q	0.25	9300 ± 518	26.80 ± 7.72	-0.0822 ± 0.0237	11467 ± 326	.	12135	10800	177	229	163
2015	MO	H	AP	ns	0.04	6547 ± 799	6.40 ± 4.30ns	ns	7800 ± 343	.	9680	6903	272	.	.
2015	MO	H	S	ns	-0.03	6682 ± 817	2.32 ± 4.49ns	ns	7178 ± 242	.	9161	5661	315	.	.
2015	MO	L	AP	L	0.59	3341 ± 545	18.61 ± 2.83b	ns	9183 ± 517a	.	10243	8124	315	.	.
2015	MO	L	S	QP	0.68	2651 ± 505	36.47 ± 8.54	-0.0695 ± 0.0296	7435 ± 367b	7435 ± 367	.	6683	315	262	166
2016	MO	HA	AP	Q	0.35	8975 ± 521	22.43 ± 7.77	-0.0452 ± 0.0238	11755 ± 294	.	12356	11153	239	299	227
2016	MO	HA	S	Q	0.35	8804 ± 425	22.11 ± 6.35	-0.0513 ± 0.0194	11183 ± 254	.	11702	10663	205	252	191
2016	MO	HB	AP	Q	0.50	7860 ± 673	42.16 ± 10.04	-0.0913 ± 0.0308	12663 ± 396a	.	13473	11853	258	283	245
2016	MO	HB	S	QP	0.57	7829 ± 474	31.76 ± 9.53	-0.0712 ± 0.0380	11353 ± 241b	11371 ± 292	.	10860	207	223	125
2016	MO	L	AP	Q	0.10	6178 ± 369	12.05 ± 5.51	-0.0394 ± 0.0169	7096 ± 236	.	7578	6613	164	.	.
2016	MO	L	S	L	0.20	5983 ± 263	4.11 ± 1.40	ns	6770 ± 152	.	7080	6459	191	269	269
2014	ND	H	AP	L	0.38	6292 ± 518	12.24 ± 2.76	ns	8390 ± 287a	.	8975	7804	171	306	155
2014	ND	H	S	L	0.26	6312 ± 475	8.71 ± 2.53	ns	7741 ± 261b	.	8273	7209	164	.	.
2014	ND	L	AP	Q	0.44	1549 ± 650	43.31 ± 9.70a	-0.1073 ± 0.0297	5856 ± 410a	.	6695	5017	177	209	164
2014	ND	L	S	L	0.11	2663 ± 664	7.77 ± 3.54b	ns	3947 ± 365b	.	4693	3202	165	.	.
2015	ND	H	AP	Q	0.50	3582 ± 517	26.26 ± 7.71	-0.0477 ± 0.0236	6867 ± 318	.	7517	6218	192	245	178
2015	ND	H	S	QP	0.57	3252 ± 469	52.10 ± 17.20	-0.2053 ± 0.1204	6558 ± 213	6558 ± 213	.	6123	155	127	65
2015	ND	L	AP	Q	0.39	3924 ± 604	34.30 ± 9.01	-0.0806 ± 0.0276	6573 ± 354	.	7297	5849	101	135	133
2015	ND	L	S	QP	0.60	3673 ± 397	32.80 ± 9.75	-0.0886 ± 0.0466	6522 ± 234	6709 ± 216	.	6042	139	185	91
2016	ND	H	AP	ns	-0.03	7586 ± 270	-0.50 ± 1.44ns	ns	7508 ± 68	.	8136	7035	45	.	.
2016	ND	H	S	ns	-0.03	7575 ± 364	-0.32 ± 1.94ns	ns	7524 ± 116	.	8318	6831	45	.	.
2016	ND	L	AP	ns	-0.03	6440 ± 251	0.28 ± 1.34ns	ns	6484 ± 92	.	6952	5928	0	.	.
2016	ND	L	S	ns	-0.03	6643 ± 295	-0.24 ± 1.57ns	ns	6604 ± 124	.	7245	6041	0	57	-43

Table 15. Continued.

Year	State	Prod.	T	Model†	Adj. R^2	a	bx	cx^2‡	SDM_E	SDM Plateau	UCLM	LCLM	EONR	UCLM	LCLM
									---------------- kg DM ha^{-1} ----------------				---- kg N ha^{-1} ----		
2014	NE	H	AP	L	0.33	8474 ± 273	5.88 ± 1.45	ns	9033 ± 174b	.	9389	8677	114	168	83
2014	NE	H	S	Q	0.39	8209 ± 303	12.97 ± 4.53	-0.0243 ± 0.0139	9537 ± 192a	.	9929	9145	157	220	123
2014	NE	L	AP	Q	0.38	4134 ± 609	27.68 ± 9.08	-0.0558 ± 0.0278	7440 ± 490	.	8441	6438	307	.	.
2014	NE	L	S	Q	0.37	4003 ± 489	23.95 ± 7.29	-0.0519 ± 0.0223	6730 ± 292	.	7327	6132	217	259	191
2015	NE	H	AP	L	0.23	8052 ± 343	5.92 ± 1.83a	ns	8210 ± 303	.	8829	7591	46	134	134
2015	NE	H	S	L	0.13	8166 ± 190	2.37 ± 1.01b	ns	8230 ± 167	.	8572	7888	46	134	134
2015	NE	L	AP	L	0.70	3228 ± 210	9.54 ± 1.12b	ns	6221 ± 210a	.	6649	5793	315	.	.
2015	NE	L	S	QP	0.55	3116 ± 243	17.29 ± 5.59	-0.0439 ± 0.0253	4818 ± 139b	4818 ± 139	.	4534	198	197	107
2016	NE	H	AP	L	0.17	5209 ± 176	2.56 ± 0.94b	ns	5304 ± 148	.	5607	5001	56	134	134
2016	NE	H	S	Q	0.26	4938 ± 230	10.54 ± 3.43a	-0.0256 ± 0.0105	5292 ± 154	.	5606	4978	56	64	15
2016	NE	L	AP	Q	0.38	6547 ± 525	26.73 ± 7.84a	-0.0583 ± 0.0240	9456 ± 331a	.	10134	8779	185	232	163
2016	NE	L	S	L	0.32	7192 ± 344	7.30 ± 1.83b	ns	8332 ± 188b	.	8717	7948	163	.	.
2014	WI	H	AP	Q	0.37	7461 ± 385	25.71 ± 5.75a	-0.0729 ± 0.0176b	9325 ± 226a	.	9788	8863	102	128	90
2014	WI	H	S	Q	0.16	7469 ± 324	12.90 ± 4.84b	-0.0343 ± 0.0148a	8261 ± 183b	.	8635	7888	77	133	66
2014	WI	L	AP	Q	0.24	6794 ± 343	17.16 ± 5.11a	-0.0473 ± 0.0157	8265 ± 217	.	8708	7822	139	193	124
2014	WI	L	S	ns	0.00	7510 ± 319	1.63 ± 1.70bns	ns	7766 ± 279	.	8085	7323	119	.	.
2015	WI	H	AP	Q	0.13	6325 ± 270	9.49 ± 4.03a	-0.0245 ± 0.0123	6325 ± 270	.	6877	5773	0	38	-72
2015	WI	H	S	ns	-0.01	6653 ± 203	0.91 ± 1.15bns	ns	6775 ± 118	.	7069	6237	0	63	-21
2015	WI	L	AP	QP	0.58	5405 ± 302	16.88 ± 4.92	-0.0299 ± 0.0162	7783 ± 210a	7789 ± 253	.	7354	268	283	167
2015	WI	L	S	Q	0.44	5482 ± 256	16.90 ± 3.82	-0.0418 ± 0.0117	7157 ± 162b	.	7488	6826	174	206	161
2016	WI	H	AP	ns	0.07	6363 ± 306	8.93 ± 4.46	-0.0247 ± 0.0136	7033 ± 179	.	7400	6666	107	.	.
2016	WI	H	S	L	0.13	6708 ± 217	2.62 ± 1.14	ns	7084 ± 118	.	7325	6842	144	.	.
2016	WI	L	AP	ns	-0.03	5098 ± 413	0.07 ± 2.19ns	ns	5102 ± 156	.	5703	4504	73	.	.
2016	WI	L	S	ns	-0.03	5138 ± 339	-0.27 ± 1.81ns	ns	5096 ± 111	.	5594	4640	79	.	.

Level of significant for the regression model. ns = not significant; * = $p \leq 0.10$

† Not significant model, intercept, and/or slope SDM_E was reported as the average SDM across all N rates used in the model.

‡ Quadratic coefficient non-significant (ns) then linear regression used.

Table 16. Correlation (r) between different periods of total rainfall (TR) or abundance and well-distribution of rainfall (AWDR) with internal N efficiency at the economic optimum N rate (IE_E) for eight states in and across three years (2014, 2015, and 2016), two productivity sites (high and low based on historical yield data), and N application timings (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage). Significant correlations ($p \leq 0.10$) with * and bolded.

Periods of Total Rainfall Variables	All	2014	2015	2016
	r			
Ten days Before N Applied At-Planting (TR_{10dBPN})	-0.12	-0.28	0.05	-0.04
Ten days After N Applied At-Planting (TR_{10dAPN})	-0.04	-0.07	**-0.63***	0.18
Ten days Before and After N Applied At-Planting ($TR_{10dBAPN}$)	-0.12	**-0.34***	-0.27	0.11
Ten days Before N Split-Applied (TR_{10dBSN})	-0.07	-0.16	0.28	-0.10
Ten days After N Split-Applied (TR_{10dASN})	0.17	-0.08	**0.47***	0.23
Ten days Before and After N Split-Applied ($TR_{10dBASN}$)	0.04	-0.14	**0.44***	0.14
Vegetative Growth (TR_{Vege})	0.02	**0.42***	-0.03	-0.18
Two-weeks Before Tasseling (TR_{2wkBVT})	0.10	0.18	0.07	-0.06
Two-weeks After Tasseling (TR_{2wkAVT})	-0.13	0.15	0.24	**-0.43***
Two-weeks Before and After Tasseling ($TR_{2wkBAVT}$)	-0.00	0.23	0.20	**-0.37***
Grain Fill (TR_{GF})	0.09	0.26	0.10	-0.06
Growing Season (TR_{GS})	0.08	**0.40***	0.04	-0.14
Abundance and well-distribution of rainfall (AWDR)				
Ten days Before N Applied At-Planting ($AWDR_{10dBPN}$)	-0.14	-0.20	-0.10	-0.09
Ten days After N Applied At-Planting ($AWDR_{10dAPN}$)	0.05	0.06	**-0.65***	0.22
Ten days Before and After N Applied At-Planting ($AWDR_{10dBAPN}$)	-0.17	**-0.40***	**-0.33***	0.02
Ten days Before N Split-Applied ($AWDR_{10dBSN}$)	-0.13	-0.14	0.10	-0.13
Ten days After N Split-Applied ($AWDR_{10dASN}$)	**0.18***	0.04	**0.48***	0.18
Ten days Before and After N Split-Applied ($AWDR_{10dBASN}$)	0.04	-0.10	**0.44***	0.19
Vegetative Growth ($AWDR_{Vege}$)	0.07	**0.55***	-0.05	-0.17
Two-weeks Before Tasseling ($AWDR_{2wkBVT}$)	0.16	0.17	0.13	0.06
Two-weeks After Tasseling ($AWDR_{2wkAVT}$)	**-0.28***	0.07	0.32	**-0.60***
Two-weeks Before and After Tasseling ($AWDR_{2wkBAVT}$)	0.04	**0.39***	0.23	**-0.40***
Grain Fill ($AWDR_{GF}$)	0.08	**0.31***	0.06	-0.08
Growing Season ($AWDR_{GS}$)	0.08	**0.42***	-0.02	-0.15

Table 17. Correlation (r) between different periods of mean high (HT) and low temperature (LT) (°C) with internal N efficiency at the economic optimum N rate (IE_E) for eight states in and across three years (2014, 2015, and 2016), two productivity sites (high and low based on historical yield data) and N application timings (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage). Significant correlations ($p \leq 0.10$) with * and bolded.

Temperature Variables	All	2014	2015	2016
Mean High Temperature	r			
Vegetative Growth (HT_{Vege})	0.11	**-0.41***	**0.42***	0.22
Two-weeks Before Tasseling (HT_{2wkBVT})	0.05	**-0.34***	-0.10	0.27
Two-weeks After Tasseling (HT_{2wkAVT})	**-0.20***	**-0.44***	**0.39***	**-0.55***
Two-weeks Before and After Tasseling ($HT_{2wkBAVT}$)	-0.09	**-0.39***	0.15	-0.26
Grain Fill (HT_{GF})	-0.16	**-0.41***	**0.41***	**-0.52***
Growing Season (HT_{GS})	-0.05	**-0.42***	**0.47***	-0.19
Mean Low Temperature				
Vegetative Growth (LT_{Vege})	-0.01	-0.19	0.13	0.07
Two-weeks Before Tasseling (LT_{2wkBVT})	0.01	-0.12	-0.05	-0.03
Two-weeks After Tasseling (LT_{2wkAVT})	-0.04	-0.07	0.25	**-0.57***
Two-weeks Before and After Tasseling ($LT_{2wkBAVT}$)	-0.03	-0.11	0.14	**-0.32***
Grain Fill (LT_{GF})	-0.14	-0.18	0.23	**-0.47***
Growing Season (LT_{GS})	-0.08	-0.19	0.20	-0.22

Table 18. Mean high and low temperature (°C) at different times during the growing season for eight state over a three year period (2014, 2015, and 2016) and two productivity sites (Prod. - high (H) and low (L) based on historical data) during vegetative period (Vege.), two weeks before tasseling (2wkBVT), two weeks after tasseling (2wkAVT), two weeks before and after tasseling (2wkBAVT), grain fill and the whole growing season.

			Periods during the growing season											
			High						Low					
Year	State	Prod.	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season
			Mean Temperature (°C)											
2014	IA	H	25	26	27	27	25	25	14	15	14	15	12	13
2014	IA	L	25	26	27	27	25	25	14	15	15	15	13	14
2014	IL	H	26	29	28	29	29	27	14	18	15	16	16	15
2014	IL	L	27	31	29	30	29	28	15	20	16	18	17	16
2014	IN	H	27	26	27	26	26	26	14	14	12	13	12	13
2014	IN	L	27	26	26	26	25	26	15	14	13	13	13	14
2014	MN	H	26	26	27	27	25	25	15	15	15	15	14	14
2014	MN	L	26	27	28	27	26	26	14	15	14	15	13	14
2014	MO	H	28	32	30	31	32	30	16	20	16	18	17	17
2014	MO	L	27	30	30	30	31	29	16	18	16	17	17	17
2014	ND	H	26	27	28	28	25	25	14	14	13	14	11	13
2014	ND	L	26	27	28	28	25	25	14	14	12	13	11	12
2014	NE	L	27	29	28	28	27	27	13	16	15	15	15	14
2014	NE	H	26	29	30	30	28	27	12	15	15	15	14	13
2014	WI	H	26	27	27	27	26	26	12	13	13	13	12	12
2014	WI	L	25	26	26	26	25	25	14	15	16	16	14	14

Table 18. Continued.

			Periods during the growing season											
			High						Low					
Year	State	Prod.	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season	Vege.	2wk-BVT	2wk-AVT	2wk-BAVT	Grain Fill	Growing Season
			Mean Temperature (°C)											
2015	IA	H	25	29	30	30	27	26	14	19	18	19	16	15
2015	IA	L	26	28	28	28	26	26	15	18	17	17	15	15
2015	IL	H	25	25	29	27	30	27	14	15	18	16	16	15
2015	IL	L	27	28	31	29	30	28	16	18	21	19	18	17
2015	IN	H	25	27	30	28	27	26	13	15	15	15	13	13
2015	IN	L	25	27	30	29	27	26	13	16	16	16	14	13
2015	MN	H	23	28	29	28	26	24	11	16	15	15	13	12
2015	MN	L	23	27	28	28	26	24	12	16	16	16	15	13
2015	MO	H	26	30	30	30	32	28	14	20	19	20	19	16
2015	MO	L	25	27	31	29	30	27	15	18	22	20	19	17
2015	ND	H	23	29	28	28	27	24	10	16	14	15	13	11
2015	ND	L	24	29	28	29	27	25	11	16	15	15	14	12
2015	NE	H	25	31	30	30	29	27	13	19	18	18	16	14
2015	NE	L	25	30	30	30	29	26	12	18	17	18	15	13
2015	WI	H	24	28	28	28	26	25	13	16	15	16	13	13
2015	WI	L	24	28	28	28	26	25	13	17	15	16	14	13

Table 18. Continued.

Year	State	Prod.	High: Vege.	High: 2wk-BVT	High: 2wk-AVT	High: 2wk-BAVT	High: Grain Fill	High: Growing Season	Low: Vege.	Low: 2wk-BVT	Low: 2wk-AVT	Low: 2wk-BAVT	Low: Grain Fill	Low: Growing Season
			Periods during the growing season											
			---- Mean Temperature (°C) ----											
2016	IA	H	27	29	31	30	29	28	14	17	19	18	17	15
2016	IA	L	28	28	30	29	27	28	15	17	18	17	15	15
2016	IL	H	26	32	29	30	31	29	14	19	16	17	18	16
2016	IL	L	27	33	29	31	32	29	15	21	17	19	19	17
2016	IN	H	29	30	30	30	28	28	15	16	17	16	15	15
2016	IN	L	29	30	30	30	28	28	15	17	18	17	16	16
2016	MN	H	25	31	29	30	28	26	12	18	16	17	15	13
2016	MN	L	26	28	28	28	27	26	14	17	17	17	15	14
2016	MO	HA	25	29	33	31	31	28	14	19	20	20	20	16
2016	MO	HB	28	31	35	33	33	30	14	19	20	20	20	16
2016	MO	L	26	31	29	30	30	27	14	20	19	20	20	17
2016	ND	H	26	30	28	29	28	26	12	15	15	15	13	12
2016	ND	L	26	29	29	29	27	26	12	15	16	15	13	12
2016	NE	H	29	32	32	32	28	28	15	20	18	19	15	15
2016	NE	L	29	32	30	31	29	29	14	19	17	18	16	15
2016	WI	H	25	29	30	30	28	26	11	15	16	16	14	12
2016	WI	L	25	29	30	30	28	26	11	15	16	16	14	12

Table 19. Correlation (r) between soil texture, weighted mean for organic matter in Ap horizon (OM_2 and OM_3) and routine OM taken at 0-15 cm depth (ROM), and plant available water content (retrieved from the SSURGO data base) determined at 0-30 (PAWC0-30), 30-60 (PAWC30-60), and 60-90 cm (PAWC60-90) soil depth and average over each depth (PAWC0-90) with internal N efficiency at the economic optimum N rate (IE_E) for eight states in and across three years (2014, 2015, and 2016), two productivity sites (high and low based on historical yield data), and N application timings (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage). Significant correlations ($p \leq 0.10$) with * and bolded.

Soil Variables	All	2014	2015	2016
Soil Properties	r			
Silt Content	**-0.22***	0.07	**-0.33***	**-0.37***
Sand Content	**0.24***	-0.07	**0.33***	**0.40***
Clay Content	-0.17	0.04	-0.29	-0.26
Weighted Mean Ap Organic Matter Content (OM_2) †	0.15	**0.40***	-0.30	0.23
Weighted Mean Ap Organic Matter Content (OM_3) ‡	0.13	**0.41***	**-0.33***	0.19
Routine Organic Matter Content at 15 cm depth (ROM)§	0.05	**0.44***	**-0.69***	0.18
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	**-0.30***	-0.25	**-0.40***	**-0.29***
SSURGO Plant Available Water Content at the 30-60 cm depth (PAWC30-60)	**-0.25***	0.07	-0.31	**-0.36***
SSURGO Plant Available Water Content at the 60-90 cm depth (PAWC60-90)	**-0.34***	-0.20	**-0.34***	**-0.34***
SSURGO Plant Available Water Content averaged over the 0-30,30-60, and 60-90 cm depth (PAWC0-90)	**-0.36***	-0.16	**-0.39***	**-0.40***

† OM_2 = Van Bemmelen's factor (OM = TOC * 1.72) (Nelson and Sommers, 1996);
‡ OM_3 = Thermo Gravimetric Analyzer (TGA) with 150°C drying temperature and 360°C burn off temperature.
§ ROM = Determined from: IA = Dry Combustion, IL = Loss on Ignition, IN = Loss on Ignition, MN = Loss on Ignition, MO = Loss on Ignition, ND = Loss on Ignition, NE = Loss on Ignition, WI = Loss on Ignition.

Table 20. Soil texture, weighted mean for organic matter in Ap horizon (OM_2 and OM_3) routine OM taken at the 0-15 cm depth (ROM) (±standard deviation), and plant available water content (retrieved from the SSURGO data base) at the 0-30 (PAWC0-30), 30-60 (PAWC30-60), and 60-90 cm (PAWC60-90) depth and 0-90 cm depth (PAWC0-90: average over the 0-30, 30-60, and 60-90 cm depths) for eight state over a three year period and two productivity sites (Prod. - high (H) and low (L) based on historical yield data). Standard deviation based on four replicated soil samples.

Year	State	Prod.	clay	silt	sand	OM_2†	OM_3‡	ROM§	PAWC0-30	PAWC30-60	PAWC60-90	PAWC0-90
			----------	----------	---------- g kg^{-1}	----------	----------	----------	----------	---------- cm cm^{-1}	----------	----------
2014	IA	H	257 ± 16	412 ± 33	331 ± 49	35 ± 4	38 ± 4	44	0.21	0.19	0.17	0.19
2014	IA	L	201 ± 53	304 ± 27	496 ± 77	25 ± 7	27 ± 7	30	0.20	0.18	0.18	0.19
2014	IL	H	313 ± 12	579 ± 26	108 ± 26	30 ± 3	31 ± 3	33	0.20	0.16	0.15	0.17
2014	IL	L	301 ± 15	578 ± 18	121 ± 17	11 ± 4	16 ± 3	19	0.22	0.18	0.15	0.18
2014	IN	H	146 ± 28	217 ± 54	637 ± 81	22 ± 5	22 ± 5	26	0.17	0.17	0.17	0.17
2014	IN	L	88 ± 31	217 ± 8	695 ± 26	14 ± 1	15 ± 1	15	0.16	0.14	0.14	0.15
2014	MN	H	268 ± 45	392 ± 89	340 ± 126	64 ± 17	56 ± 14	69	0.20	0.18	0.15	0.18
2014	MN	L	248 ± 15	711 ± 16	41 ± 13	24 ± 7	26 ± 5	31	0.22	0.21	0.21	0.21
2014	MO	H	191 ± 22	610 ± 28	199 ± 47	15 ± 1	16 ± 2	14	0.23	0.21	0.21	0.22
2014	MO	L	363 ± 17	595 ± 6	42 ± 12	20 ± 3	24 ± 2	21	0.23	0.12	0.18	0.18
2014	ND	H	219 ± 19	456 ± 38	326 ± 43	36 ± 7	34 ± 5	42	0.22	0.16	0.14	0.17
2014	ND	L	668 ± 71	266 ± 48	66 ± 26	43 ± 2	36 ± 7	59	0.16	0.15	0.15	0.15
2014	NE	L	363 ± 10	561 ± 20	76 ± 19	16 ± 5	16 ± 4	n/a	0.21	0.15	0.15	0.17
2014	NE	H	69 ± 7	92 ± 6	838 ± 3	26 ± 1	27 ± 1	33	0.10	0.12	0.20	0.14
2014	WI	H	237 ± 8	719 ± 16	45 ± 23	30 ± 1	31 ± 1	39	0.23	0.23	0.23	0.23
2014	WI	L	298 ± 44	665 ± 44	37 ± 3	24 ± 3	27 ± 3	40	0.22	0.20	0.20	0.21

Table 20. Continued.

Year	State	Prod.	clay	silt	sand	OM_2†	OM_3‡	ROM§	PAWC0-30	PAWC30-60	PAWC60-90	PAWC0-90
			------------------------------ g kg^{-1} ------------------------------						------------------------ cm cm^{-1} ------------------------			
2015	IA	H	329 ± 7	648 ± 8	23 ± 2	28 ± 5	32 ± 4	36	0.22	0.22	0.19	0.21
2015	IA	L	214 ± 35	299 ± 33	487 ± 68	28 ± 3	30 ± 3	34	0.20	0.18	0.18	0.19
2015	IL	H	312 ± 17	598 ± 49	90 ± 48	27 ± 1	31 ± 1	30	0.20	0.16	0.15	0.17
2015	IL	L	293 ± 11	592 ± 17	115 ± 27	14 ± 1	18 ± 1	17	0.22	0.18	0.15	0.18
2015	IN	H	152 ± 17	230 ± 24	618 ± 37	29 ± 3	29 ± 3	31	0.17	0.17	0.17	0.17
2015	IN	L	93 ± 9	242 ± 15	665 ± 23	14 ± 2	16 ± 1	18	0.16	0.14	0.14	0.15
2015	MN	H	322 ± 62	462 ± 93	216 ± 146	59 ± 10	54 ± 9	21	0.18	0.17	0.17	0.17
2015	MN	L	246 ± 20	711 ± 23	43 ± 3	26 ± 3	27 ± 2	52	0.22	0.21	0.21	0.21
2015	MO	H	205 ± 50	427 ± 85	368 ± 130	31 ± 0	35 ± 0	16	0.22	0.22	0.20	0.21
2015	MO	L	355 ± 30	612 ± 29	32 ± 5	21 ± 3	26 ± 2	23	0.23	0.12	0.18	0.18
2015	ND	H	157 ± 48	450 ± 72	393 ± 108	22 ± 5	21 ± 3	41	0.16	0.14	0.15	0.15
2015	ND	L	464 ± 52	483 ± 52	53 ± 5	47 ± 3	42 ± 2	68	0.16	0.15	0.15	0.15
2015	NE	H	350 ± 17	575 ± 14	75 ± 3	30 ± 3	31 ± 2	36	0.21	0.15	0.15	0.17
2015	NE	L	21 ± 9	69 ± 9	910 ± 17	11 ± 1	11 ± 2	11	0.10	0.07	0.07	0.08
2015	WI	H	251 ± 18	714 ± 18	34 ± 3	34 ± 7	35 ± 5	34	0.23	0.21	0.19	0.21
2015	WI	L	341 ± 67	578 ± 72	81 ± 106	38 ± 3	41 ± 2	45	0.21	0.14	0.10	0.15

Table 20. Continued.

Year	State	Prod.	clay	silt	sand	OM_2†	OM_3‡	ROM§	PAWC0-30	PAWC30-60	PAWC60-90	PAWC0-90
			----------------------------- $g\ kg^{-1}$ -----------------------------						----------------------- $cm\ cm^{-1}$ -----------------------			
2016	IA	H	355 ± 10	621 ± 8	24 ± 3	35 ± 3	35 ± 3	45	0.22	0.20	0.19	0.20
2016	IA	L	231 ± 54	343 ± 43	426 ± 96	32 ± 11	32 ± 9	42	0.21	0.19	0.18	0.19
2016	IL	H	294 ± 60	591 ± 82	116 ± 130	32 ± 4	34 ± 3	38	0.20	0.16	0.15	0.17
2016	IL	L	273 ± 6	627 ± 27	100 ± 26	20 ± 2	22 ± 2	25	0.22	0.18	0.15	0.18
2016	IN	H	162 ± 23	272 ± 36	567 ± 56	36 ± 8	46 ± 11	47	0.17	0.17	0.17	0.17
2016	IN	L	90 ± 19	235 ± 20	675 ± 33	17 ± 2	18 ± 1	18	0.16	0.14	0.14	0.15
2016	MN	H	39 ± 14	62 ± 18	899 ± 31	22 ± 5	21 ± 5	18	0.20	0.19	0.17	0.19
2016	MN	L	336 ± 37	466 ± 24	198 ± 60	51 ± 5	47 ± 3	57	0.10	0.10	0.08	0.09
2016	MO	HA	267 ± 8	691 ± 7	42 ± 4	24 ± 1	27 ± 2	24	0.23	0.19	0.19	0.20
2016	MO	HB	290 ± 51	482 ± 61	228 ± 106	22 ± 2	24 ± 1	20	0.22	0.22	0.20	0.21
2016	MO	L	341 ± 11	625 ± 8	34 ± 4	15 ± 2	20 ± 2	19	0.22	0.13	0.11	0.15
2016	ND	H	216 ± 7	477 ± 12	306 ± 8	34 ± 2	30 ± 2	41	0.22	0.16	0.14	0.17
2016	ND	L	653 ± 80	273 ± 48	74 ± 32	40 ± 3	39 ± 2	56	0.16	0.15	0.15	0.15
2016	NE	H	334 ± 10	590 ± 9	76 ± 2	30 ± 2	32 ± 2	33	0.23	0.17	0.18	0.19
2016	NE	L	221 ± 34	384 ± 57	394 ± 89	24 ± 4	24 ± 3	24	0.22	0.17	0.01	0.13
2016	WI	H	280 ± 8	699 ± 12	21 ± 5	34 ± 5	37 ± 4	37	0.23	0.21	0.20	0.21
2016	WI	L	285 ± 52	492 ± 51	223 ± 100	44 ± 8	49 ± 7	49	0.20	0.08	0.05	0.11

† OM_2 = Van Bemmelen's factor (OM = TOC * 1.72). (Nelson and Sommers, 1996)
‡ OM_3 = Used a Thermo Gravimetric Analyzer (TGA) with 150°C drying temperature and 360°C burn off temperature.
§ ROM = Determined from: IA = Dry Combustion, IL = Loss on Ignition, IN = Loss on Ignition, MN = Loss on Ignition, MO = Loss on Ignition, ND = Loss on Ignition, NE = Loss on Ignition, WI = Loss on Ignition.
n/a = Soil samples not taken.

Table 21. Pre-plant soil NO_3-N at the 0-30, 30-60, and 60-90 cm depths (PPNT0-30, PPNT30-60, and PPNT60-90) and pre-sidedress soil NO_3-N (± standard deviation) taken at the V5±1 V-stage from the 0 and 45 kg N ha^{-1} treatments at 0-30 ($PSNT_0$0-30 and $PSNT_{45}$0-30) and 30-60 cm depths ($PSNT_0$30-60 and $PSNT_{45}$30-60) for eight states over a three years period (2014, 2015, and 2016) and two productivity sites (Prod. – high (H) and low (L) based on historical yield data). Average soil NO_3-N across 0-30 and 30-60 cm depths was determined for both timing (PPNT0-60) and N rates ($PSNT_0$0-60 and $PSNT_{45}$0-60).

Year	State	Prod.	PPNT 0-30	PPNT 30-60	PPNT 0-60	PPNT 60-90	$PSNT_0$ 0-30	$PSNT_{45}$ 0-30	$PSNT_0$ 30-60	$PSNT_{45}$ 30-60	$PSNT_0$ 0-60	$PSNT_{45}$ 0-60
			----------	----------	----------	----------	---------- NO_3-N mg kg^{-1} ----------	----------	----------	----------	----------	----------
2014	IA	H	4.3 ± 0.5	3.4 ± 0.3	3.8 ± 0.3	3.3 ± 0.5	7.0 ± 2.7	18.0 ± 3.9	3.9 ± 2.4	5.0 ± 1.8	5.4 ± 0.2	11.5 ± 2.1
2014	IA	L	6.3 ± 1.3	5.5 ± 0.9	5.9 ± 1.1	3.5 ± 0.6	8.6 ± 2.4	12.5 ± 1.4	5.8 ± 2.1	6.1 ± 1.9	7.2 ± 2.2	9.3 ± 1.5
2014	IL	H	6.5 ± 0.7	4.8 ± 1.0	5.6 ± 0.6	3.3 ± 0.3	9.5 ± 1.8	19.9 ± 2.3	6.8 ± 2.3	10.4 ± 2.5	8.1 ± 1.4	15.1 ± 1.9
2014	IL	L	4.6 ± 0.6	3.5 ± 0.7	4.1 ± 0.6	2.0 ± 0.6	7.5 ± 2.2	12.3 ± 3.7	6.1 ± 4.0	12.9 ± 5.6	6.8 ± 3.0	12.6 ± 4.3
2014	IN	H	5.5 ± 0.0	3.6 ± 0.3	4.6 ± 0.1	2.6 ± 0.3	7.6 ± 1.3	11.5 ± 2.4	4.8 ± 1.2	5.5 ± 1.3	6.2 ± 1.0	8.5 ± 1.7
2014	IN	L	11.3 ± 2.3	3.8 ± 0.3	7.5 ± 1.2	2.8 ± 0.3	12.0 ± 4.2	18.9 ± 5.2	4.4 ± 0.5	7.6 ± 2.5	8.2 ± 2.2	13.3 ± 2.8
2014	MN	H	3.8 ± 0.3	4.0 ± 0.7	3.9 ± 0.4	3.6 ± 0.8	7.6 ± 2.7	14.8 ± 5.4	5.1 ± 1.1	7.0 ± 2.5	6.4 ± 1.9	10.9 ± 3.5
2014	MN	L	2.0 ± 0.6	2.8 ± 1.0	2.4 ± 0.8	2.4 ± 1.0	7.6 ± 5.4	13.8 ± 3.5	4.6 ± 1.3	6.3 ± 1.2	6.1 ± 3.1	10 ± 1.3
2014	MO	H	5.4 ± 0.9	4.9 ± 0.6	5.1 ± 0.8	4.9 ± 0.5	4.8 ± 0.9	12.1 ± 1.3	5.6 ± 0.9	9.4 ± 3.9	5.2 ± 0.4	10.8 ± 2.4
2014	MO	L	6.4 ± 1.1	4.5 ± 0.7	5.4 ± 0.9	3.1 ± 0.3	5.1 ± 1.1	13.5 ± 6.4	6.5 ± 1.7	12.8 ± 7.3	5.8 ± 1.3	13.1 ± 6.6
2014	ND	H	1.5 ± 0.4	1.6 ± 0.5	1.6 ± 0.4	0.6 ± 0.3	2.9 ± 0.3	9.1 ± 1.1	n/a†	n/a	n/a	n/a
2014	ND	L	3.5 ± 0.0	4.3 ± 1.2	3.9 ± 0.6	3.5 ± 1.2	2.8 ± 0.3	4.3 ± 1.0	4.0 ± 2.8	3.3 ± 0.4	3.4 ± 1.6	3.4 ± 0.2
2014	NE	H	14.5 ± 1.1	5.5 ± 1.6	10.0 ± 1.3	3.5 ± 0.6	17.1 ± 4.6	21.3 ± 6.6	13.5 ± 2.7	15.0 ± 5.0	15.3 ± 3.6	18.1 ± 5.8
2014	NE	L	5.5 ± 0.4	3.1 ± 1.0	4.3 ± 0.6	2.6 ± 1.1	4.4 ± 1.5	8.3 ± 3.4	n/a	n/a	n/a	n/a
2014	WI	H	4.6 ± 2.9	3.6 ± 0.8	4.1 ± 1.8	3.9 ± 0.8	6.9 ± 1.9	11.8 ± 3.6	4.1 ± 0.9	7.5 ± 1.8	5.5 ± 1.1	9.6 ± 2.5
2014	WI	L	4.5 ± 0.7	3.6 ± 0.3	4.1 ± 0.3	1.6 ± 0.3	7.4 ± 1.3	12.1 ± 3.4	5.4 ± 1.3	7.1 ± 1.9	6.4 ± 0.9	9.6 ± 2.6

Table 21. Continued.

Year	State	Prod.	PPNT 0-30	PPNT 30-60	PPNT 0-60	PPNT 60-90	$PSNT_0$ 0-30	$PSNT_{45}$ 0-30	$PSNT_0$ 30-60	$PSNT_{45}$ 30-60	$PSNT_0$ 0-60	$PSNT_{45}$ 0-60
			------------------ NO_3-N mg kg^{-1} ------------------									
2015	IA	H	7.0 ± 0.4	3.0 ± 0.0	5.0 ± 0.2	1.8 ± 0.3	6.8 ± 1.8	14.3 ± 4.3	6.1 ± 1.3	9.0 ± 2.9	6.4 ± 1.5	11.6 ± 3.6
2015	IA	L	4.0 ± 1.0	2.3 ± 0.3	3.1 ± 0.6	1.6 ± 0.3	3.9 ± 0.9	8.9 ± 2.6	3.8 ± 0.3	7.6 ± 1.4	3.8 ± 0.5	8.3 ± 1.6
2015	IL	H	10.5 ± 0.7	6.4 ± 1.2	8.4 ± 0.7	3.3 ± 0.3	16.1 ± 1.4	23.3 ± 3.3	10.6 ± 1.7	17.1 ± 6.3	13.4 ± 1.1	20.2 ± 4.4
2015	IL	L	2.3 ± 0.3	1.5 ± 0.0	1.9 ± 0.1	1.1 ± 0.3	6.0 ± 0.7	13.1 ± 3.0	3.5 ± 0.6	6.4 ± 1.9	4.8 ± 0.6	9.8 ± 2.3
2015	IN	H	4.5 ± 0.4	3.5 ± 1.4	4.0 ± 0.7	2.6 ± 0.3	5.0 ± 0.9	11.5 ± 1.7	3.6 ± 0.3	5.3 ± 0.3	4.3 ± 0.6	8.4 ± 0.8
2015	IN	L	5.9 ± 0.9	3.9 ± 0.5	4.9 ± 0.6	2.9 ± 0.3	9.4 ± 0.9	20.8 ± 5.0	4.6 ± 0.5	4.9 ± 0.5	7.0 ± 0.6	12.8 ± 2.6
2015	MN	H	4.9 ± 1.3	3.9 ± 0.5	4.4 ± 0.8	2.0 ± 0.4	8.8 ± 1.3	14.5 ± 2.3	7.3 ± 0.9	11.6 ± 1.7	8.0 ± 1.1	13.1 ± 1.7
2015	MN	L	3.1 ± 0.6	2.8 ± 1.0	2.9 ± 0.7	1.3 ± 0.6	7.8 ± 1.6	13.9 ± 4.5	6.4 ± 1.8	7.9 ± 1.8	7.1 ± 1.4	10.9 ± 3.1
2015	MO	H	5.8 ± 1.0	4.9 ± 1.4	5.3 ± 1.2	4.5 ± 0.7	6.1 ± 0.9	14.1 ± 2.7	4.0 ± 1.1	8.1 ± 2.3	5.1 ± 0.9	11.1 ± 2.2
2015	MO	L	3.4 ± 0.5	2.0 ± 0.4	2.7 ± 0.1	1.1 ± 0.3	6.3 ± 1.3	7.0 ± 2.7	3.9 ± 1.1	3.8 ± 1.0	5.1 ± 1.0	5.4 ± 1.6
2015	ND	H	5.9 ± 1.5	4.1 ± 1.4	5.0 ± 1.4	4.5 ± 2.5	4.8 ± 0.9	7.0 ± 1.2	4.9 ± 1.4	8.9 ± 2.7	4.9 ± 0.9	7.9 ± 1.0
2015	ND	L	8.1 ± 1.2	7.3 ± 2.0	7.7 ± 1.5	3.5 ± 0.7	7.1 ± 5.4	11.8 ± 3.5	9.4 ± 8.1	13.3 ± 3.0	8.3 ± 6.7	12.5 ± 3.1
2015	NE	H	13.5 ± 3.1	2.6 ± 0.3	8.1 ± 1.5	3.3 ± 1.7	21.0 ± 6.6	31.3 ± 6.0	11.3 ± 2.9	10.1 ± 3.2	16.1 ± 3.6	20.7 ± 3.8
2015	NE	L	5.8 ± 1.8	3.4 ± 0.8	4.6 ± 1.3	2.8 ± 0.6	5.9 ± 0.9	6.6 ± 1.4	4.8 ± 2.9	8.5 ± 2.0	5.3 ± 1.5	7.6 ± 1.2
2015	WI	H	7.6 ± 0.6	5.8 ± 0.9	6.7 ± 0.7	10.0 ± 1.4	9.8 ± 1.8	16.4 ± 7.4	7.9 ± 1.0	9.9 ± 3.6	8.8 ± 1.1	13.1 ± 5.4
2015	WI	L	8.3 ± 1.5	5.4 ± 0.3	6.8 ± 0.8	3.8 ± 0.3	5.8 ± 1.4	11.1 ± 6.5	5.4 ± 0.6	9.0 ± 3.4	5.6 ± 1.0	10.1 ± 4.9

Table 21. Continued.

Year	State	Prod.	PPNT 0-30	PPNT 30-60	PPNT 0-60	PPNT 60-90	$PSNT_0$ 0-30	$PSNT_{45}$ 0-30	$PSNT_0$ 30-60	$PSNT_{45}$ 30-60	$PSNT_0$ 0-60	$PSNT_{45}$ 0-60
			--- NO_3-N mg kg^{-1} ---									
2016	IA	H	6.1 ± 1.4	4.0 ± 0.7	5.1 ± 0.8	2.5 ± 0.4	8.1 ± 2.8	11.4 ± 0.9	6.4 ± 1.5	7.3 ± 1.2	7.3 ± 2.0	9.3 ± 1.0
2016	IA	L	4.9 ± 0.8	2.1 ± 0.5	3.5 ± 0.6	1.9 ± 0.3	4.1 ± 1.3	8.4 ± 2.3	3.4 ± 0.6	4.6 ± 0.5	3.8 ± 0.9	6.5 ± 1.3
2016	IL	H	7.8 ± 1.0	4.5 ± 0.7	6.1 ± 0.7	3.4 ± 0.3	9.0 ± 2.1	19.4 ± 2.6	7.6 ± 1.7	13.3 ± 2.9	8.3 ± 1.5	16.3 ± 2.5
2016	IL	L	6.9 ± 1.6	6.0 ± 0.7	6.4 ± 1.0	4.3 ± 0.9	8.5 ± 2.7	9.4 ± 2.8	6.1 ± 1.4	6.5 ± 0.9	7.3 ± 2.0	7.9 ± 1.8
2016	IN	H	2.8 ± 0.3	2.3 ± 0.5	2.5 ± 0.4	2.1 ± 0.5	5.9 ± 0.9	11.6 ± 3.8	5.0 ± 0.8	10.4 ± 1.7	5.4 ± 0.5	11.0 ± 1.2
2016	IN	L	3.9 ± 0.5	3.6 ± 1.6	3.8 ± 1.0	2.5 ± 0.4	11.6 ± 1.4	16.8 ± 4.6	6.9 ± 1.9	10.1 ± 3.0	9.3 ± 1.6	13.4 ± 3.3
2016	MN	H	1.0 ± 0.4	0.5 ± 0.0	0.8 ± 0.2	0.5 ± 0.0	3.9 ± 0.9	17.1 ± 13.7	3.0 ± 0.8	6.4 ± 3.4	3.4 ± 0.9	11.8 ± 7.8
2016	MN	L	4.6 ± 0.9	2.9 ± 0.5	3.8 ± 0.6	2.4 ± 0.5	2.4 ± 0.8	5.8 ± 4.0	3.4 ± 0.9	6.1 ± 2.1	2.9 ± 0.8	5.9 ± 2.9
2016	MO	HA	5.0 ± 1.2	3.9 ± 0.6	4.5 ± 0.9	3.5 ± 0.0	8.3 ± 0.6	15.1 ± 3.5	6.1 ± 1.0	9.3 ± 3.2	7.2 ± 0.5	12.2 ± 3.2
2016	MO	HB	5.3 ± 0.5	3.4 ± 0.6	4.4 ± 0.4	2.8 ± 0.3	6.8 ± 2.3	10.6 ± 1.7	5.3 ± 0.6	7.1 ± 1.7	6.0 ± 1.4	8.9 ± 1.6
2016	MO	L	7.0 ± 0.7	4.5 ± 1.1	5.8 ± 0.4	2.5 ± 0.4	13.1 ± 2.7	22.0 ± 4.5	5.6 ± 1.7	6.5 ± 1.1	9.4 ± 1.3	14.3 ± 2.3
2016	ND	H	15.1 ± 3.2	4.4 ± 0.6	9.8 ± 1.9	2.5 ± 1.5	17.3 ± 4.9	20.5 ± 3.2	10.1 ± 0.5	10.9 ± 1.4	13.7 ± 2.2	15.7 ± 0.9
2016	ND	L	16.8 ± 3.5	10.7 ± 0.5	13.7 ± 1.6	7.3 ± 1.9	16.5 ± 8.1	26.9 ± 20.0	22.3 ± 14.2	12.4 ± 5.1	19.4 ± 6.3	19.6 ± 11.9
2016	NE	H	n/a	n/a	n/a	n/a	9.0 ± 1.1	11.1 ± 0.9	n/a	n/a	n/a	n/a
2016	NE	L	n/a	n/a	n/a	n/a	9.4 ± 3.3	12.0 ± 3.6	7.3 ± 2.5	10.4 ± 1.7	8.3 ± 2.9	11.2 ± 2.2
2016	WI	H	8.6 ± 1.9	4.4 ± 0.3	6.5 ± 1.0	3.3 ± 0.6	22.9 ± 7.6	29.1 ± 7.5	11.8 ± 1.9	15.3 ± 4.2	17.3 ± 4.7	22.2 ± 5.8
2016	WI	L	6.1 ± 1.1	5.0 ± 1.8	5.6 ± 0.4	25.5‡	15.9 ± 1.0	28.9 ± 3.4	10.3 ± 3.3	10.0 ± 1.4	13.1 ± 2.0	18.3 ± 2.5

† n/a = Soil samples not taken

‡ One sample taken at the 60-90 cm depth due to rocky layer.

Table 22. Correlations (r) between soil NO_3-N at pre-plant (PPNT), pre-sidedress (PSNT) taken at V5±1 V-stage, tasseling (VTNT), and post-harvest (PHNT) taken one to four weeks after harvest was determined at 0-30, 30-60, 60-90, 0-60 (averaged over the 0-30 and 30-60 cm depths), and 0-90 (averaged over the 0-30, 30-60, and 60-90 cm depths at PPNT and PHNT) depths with internal N efficiency at the economic optimum N rate (IE_E) for eight states in and across three years (2014, 2015, and 2016) and two productivity sites (high and low based on historical yield data). Also shown are the correlations between IE_E and soil NO_3-N, silt content and mean high temperature two weeks before and after tasseling ($HT_{2wkBAVT}$). Significant correlations ($p \leq 0.10$) with * and bolded.

	All	2014	2015	2016
Pre-plant Soil NO_3-N	r			
Pre-plant Soil NO_3-N 0-30 cm (PPNT0-30)	**-0.19***	-0.29	-0.21	-0.16
Pre-plant Soil NO_3-N 30-60 cm (PPNT30-60)	**-0.20***	-0.29	-0.03	-0.24
Pre-plant Soil NO_3-N 60-90 cm (PPNT60-90)	**-0.20***	-0.25	-0.12	-0.28
Pre-plant Soil NO_3-N 0-60 cm (PPNT0-60)	**-0.21***	**-0.31***	-0.17	-0.19
Pre-plant Soil NO_3-N 0-90 cm (PPNT0-90)	**0.23***	**-0.33***	-0.18	-0.21
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**-0.26***	-0.22	**-0.34***	**-0.31***
Pre-sidedress NO_3-N				
Pre-Sidedress Soil NO_3-N 0-30 cm at 0N ($PSNT_0$0-30)	-0.07	0.08	-0.08	-0.19
Pre-Sidedress Soil NO_3-N 30-60 cm at 0N ($PSNT_0$30-60)	-0.12	-0.15	-0.13	-0.14
Pre-Sidedress Soil NO_3-N 0-60 cm at 0N ($PSNT_0$0-60)	-0.10	0.01	-0.10	-0.17
Pre-Sidedress Soil NO_3-N 0-30 cm at 45N ($PSNT_{45}$0-30)	-0.05	0.15	-0.16	-0.12
Pre-Sidedress Soil NO_3-N 30-60 cm at 45N ($PSNT_{45}$30-60)	0.01	-0.21	0.17	0.04
Pre-Sidedress Soil NO_3-N 0-60 cm at 45N ($PSNT_{45}$0-60)	-0.01	0.04	-0.06	-0.02
Tasseling Soil NO_3-N				
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	0.10	**0.41***	**0.34***	-0.02
Tasseling Soil NO_3-N 30-60 cm at 0N ($VTNT_0$30-60)	0.06	**0.44***	-0.08	0.04
Tasseling Soil NO_3-N 0-60 cm at 0N ($VTNT_0$0-60)	0.05	**0.43***	0.02	0.01
Post-Harvest Soil NO_3-N				
Post-Harvest Soil NO_3-N 0-30 cm at 0N ($PHNT_0$0-30)	**-0.26***	0.04	-0.15	**-0.65***
Post-Harvest Soil NO_3-N 30-60 cm at 0N ($PHNT_0$30-60)	**-0.28***	-0.07	-0.18	**-0.45***
Post-Harvest Soil NO_3-N 60-90 cm at 0N ($PHNT_0$60-90)	-0.14	-0.18	-0.01	**-0.30***
Post-Harvest Soil NO_3-N 0-60 cm at 0N ($PHNT_0$0-60)	**-0.28***	0.00	-0.15	**-0.64***
Post-Harvest Soil NO_3-N 0-30,30-60, and 60-90 cm at 0N ($PHNT_0$0-90)	**-0.30***	-0.03	-0.15	**-0.65***
Post-Harvest Soil NO_3-N 0-30 cm at 45N ($PHNT_{45}$0-30)	**-0.29***	0.03	-0.24	**-0.63***
Post-Harvest Soil NO_3-N 30-60 cm at 45N ($PHNT_{45}$30-60)	**-0.30***	-0.02	-0.16	**-0.46***
Post-Harvest Soil NO_3-N 60-90 cm at 45N ($PHNT_{45}$60-90)	**-0.22***	-0.17	-0.05	**-0.54***
Post-Harvest Soil NO_3-N 0-60 cm at 45N ($PHNT_{45}$0-60)	**-0.32***	0.01	-0.24	**-0.61***
Post-Harvest Soil NO_3-N 0-30,30-60, and 60-90 cm at 45N ($PHNT_{45}$0-90)	**-0.33***	-0.03	-0.22	**-0.62***
$PHNT_0$0-60*Silt Content*$HT_{2wkBAVT}$	**-0.34***	-0.03	-0.30	**-0.68***
$PHNT_{45}$0-60*Silt Content*$HT_{2wkBAVT}$	**-0.37***	-0.02	**-0.37***	**-0.66***

Table 23. Soil NO3-N at tasseling (VTNT) and two to four week after harvest (PHNT) (± standard deviation) from the 0 and 45 kg N ha-1 treatments at 0-30 (VTNT00-30, PHNT00-30, and PHNT450-30), 30-60 (VTNT030-60, PHNT030-60, and PHNT4530-60), and 60-90 cm (only PHNT060-90 and PHNT4560-90) depths for eight states over a three years period (2014, 2015, and 2016) and two productivity sites (Prod. – high (H) and low (L) based on historical yield data). Average soil NO3-N across the 0-30 and 30-60 cm depth was determined for both sampling timings and N rates (VTNT00-60, PHNT00-60, and PHNT450-60).

Year	State	Prod.	$VTNT_0$ 0-30	$VTNT_0$ 30-60	$VTNT_0$ 0-60	$PHNT_0$ 0-30	$PHNT_{45}$ 0-30	$PHNT_0$ 30-60	$PHNT_{45}$ 30-60	$PHNT_0$ 0-60	$PHNT_{45}$ 0-60
			------------------------				NO_3-N mg kg^{-1}				------------------------
2014	IA	H	n/a†	n/a	n/a	5.3 ± 0.6	4.8 ± 1.3	2.0 ± 0.8	1.9 ± 0.3	3.6 ± 0.4	3.3 ± 0.6
2014	IA	L	n/a	n/a	n/a	1.4 ± 0.8	1.1 ± 0.3	0.5 ± 0.0	0.8 ± 0.3	0.9 ± 0.4	0.9 ± 0.2
2014	IL	H	4.5 ± 0.9	2.3 ± 0.5	3.4 ± 0.3	1.4 ± 0.3	1.6 ± 0.8	0.6 ± 0.3	0.8 ± 0.3	1.0 ± 0.2	1.2 ± 0.5
2014	IL	L	3.4 ± 0.7	2.8 ± 0.9	3.1 ± 0.9	0.6 ± 0.3	0.5 ± 0.0	0.5 ± 0.0	0.6 ± 0.3	0.6 ± 0.1	0.6 ± 0.1
2014	IN	H	0.5 ± 0.0	n/a	n/a	0.9 ± 0.5	0.9 ± 0.3	0.5 ± 0.0	0.5 ± 0.0	0.7 ± 0.2	0.7 ± 0.1
2014	IN	L	0.5 ± 0.0	n/a	n/a	0.5 ± 0.0	0.9 ± 0.5	0.5 ± 0.0	0.5 ± 0.0	0.5 ± 0.0	0.7 ± 0.2
2014	MN	H	2.3 ± 0.3	1.8 ± 1.4	2.1 ± 1.0	2.2 ± 1.3	1.7 ± 0.8	0.7 ± 0.3	1.0 ± 0.0	1.4 ± 0.5	1.3 ± 0.3
2014	MN	L	0.8 ± 0.6	0.5 ± 0.0	0.6 ± 0.1	1.3 ± 0.9	1.6 ± 0.6	0.5 ± 0.0	0.5 ± 0.0	0.9 ± 0.4	1.1 ± 0.3
2014	MO	H	1.5 ± 0.3	0.9 ± 0.5	1.2 ± 0.4	1.1 ± 0.8	1.3 ± 0.9	0.5 ± 0.0	0.6 ± 0.3	0.8 ± 0.4	0.9 ± 0.5
2014	MO	L	0.6 ± 0.6	0.5 ± 0.0	0.6 ± 0.1	1.6 ± 0.5	1.8 ± 0.6	0.5 ± 0.0	0.6 ± 0.3	1.1 ± 0.2	1.2 ± 0.4
2014	ND	H	1.1 ± 0.7	1.3 ± 0.6	1.2 ± 0.4	1.9 ± 0.9	1.6 ± 0.6	0.9 ± 0.5	0.6 ± 0.3	1.4 ± 0.6	1.1 ± 0.4
2014	ND	L	1.5 ± 0.3	1.3 ± 0.6	1.4 ± 0.5	1.8 ± 0.3	1.9 ± 0.5	1.8 ± 0.5	1.5 ± 0.4	1.8 ± 0.4	1.7 ± 0.4
2014	NE	H	3.6 ± 0.5	2.0 ± 0.4	2.8 ± 0.4	1.1 ± 0.3	0.9 ± 0.3	0.8 ± 0.3	0.9 ± 0.5	0.9 ± 0.1	0.9 ± 0.3
2014	NE	L	4.4 ± 0.5	n/a	n/a	1.8 ± 0.5	2.4 ± 1.3	0.5 ± 0.0	0.6 ± 0.3	1.1 ± 0.3	1.5 ± 0.6
2014	WI	H	3.3 ± 0.3	2.3 ± 0.9	2.8 ± 0.9	4.8 ± 0.3	4.3 ± 2.9	2.6 ± 0.9	2.4 ± 0.5	3.7 ± 0.5	3.3 ± 1.3
2014	WI	L	0.6 ± 2.5	0.6 ± 0.3	0.6 ± 0.1	4.8 ± 0.6	4.8 ± 1.8	1.5 ± 0.7	1.4 ± 0.8	3.1 ± 0.6	3.1 ± 1.1

Table 23. Continued.

Year	State	Prod.	$VTNT_0$ 0-30	$VTNT_0$ 30-60	$VTNT_0$ 0-60	$PHNT_0$ 0-30	$PHNT_{45}$ 0-30	$PHNT_0$ 30-60	$PHNT_{45}$ 30-60	$PHNT_0$ 0-60	$PHNT_{45}$ 0-60
			--				NO_3-N mg kg^{-1}		--		
2015	IA	H	0.6 ± 0.3	0.5 ± 0.0	0.6 ± 0.1	4.8 ± 1.9	4.4 ± 0.9	0.8 ± 0.3	0.6 ± 0.3	2.8 ± 1.1	2.5 ± 0.5
2015	IA	L	1.4 ± 0.3	0.5 ± 0.0	0.9 ± 0.1	1.6 ± 0.3	1.9 ± 0.5	0.5 ± 0.0	0.5 ± 0.0	1.1 ± 0.1	1.2 ± 0.2
2015	IL	H	2.8 ± 0.3	1.3 ± 0.3	2.0 ± 0.2	6.0 ± 1.2	5.4 ± 1.6	0.8 ± 0.3	1.0 ± 0.4	3.4 ± 0.7	3.2 ± 0.9
2015	IL	L	0.6 ± 0.3	0.5 ± 0.0	0.6 ± 0.1	2.6 ± 0.3	3.1 ± 0.9	0.6 ± 0.3	0.6 ± 0.3	1.6 ± 0.1	1.9 ± 0.3
2015	IN	H	0.9 ± 0.3	0.5 ± 0.0	0.7 ± 0.1	1.0 ± 1.0	0.8 ± 0.3	0.5 ± 0.0	0.5 ± 0.0	0.8 ± 0.5	0.6 ± 0.1
2015	IN	L	0.9 ± 0.3	1.0 ± 0.4	0.9 ± 0.3	0.6 ± 0.3	0.6 ± 0.3	0.5 ± 0.0	0.6 ± 0.3	0.6 ± 0.1	0.6 ± 0.1
2015	MN	H	1.4 ± 0.8	0.8 ± 0.3	1.1 ± 0.4	4.5 ± 0.7	5.3 ± 0.3	0.8 ± 0.3	1.1 ± 0.5	2.6 ± 0.3	3.2 ± 0.2
2015	MN	L	1.5 ± 0.5	1.0 ± 0.6	1.3 ± 0.6	4.8 ± 2.0	6.9 ± 1.3	0.6 ± 0.3	0.8 ± 0.3	2.7 ± 1.1	3.8 ± 0.5
2015	MO	H	0.9 ± 0.0	1.3 ± 0.3	1.1 ± 0.2	4.9 ± 3.4	6.6 ± 1.9	0.9 ± 0.8	1.8 ± 1.4	2.9 ± 2.1	4.2 ± 1.5
2015	MO	L	0.5 ± 0.3	0.8 ± 0.3	0.6 ± 0.1	10.1 ± 1.3	7.4 ± 2.6	1.2 ± 0.3	1.1 ± 0.3	5.8 ± 0.8	4.3 ± 1.3
2015	ND	H	n/a	n/a	n/a	1.0 ± 0.4	11.9 ± 20	0.5 ± 0.0	2.3 ± 3.5	0.8 ± 0.2	7.1 ± 12
2015	ND	L	n/a	n/a	n/a	1.0 ± 0.0	1.5 ± 0.4	1.8 ± 1.2	2.8 ± 1.6	1.4 ± 0.6	2.1 ± 0.9
2015	NE	H	1.8 ± 0.6	n/a	n/a	7.5 ± 2.0	8.4 ± 0.3	1.0 ± 0.4	1.5 ± 0.4	4.3 ± 1.1	4.9 ± 0.3
2015	NE	L	4.0 ± 1.3	n/a	n/a	3.8 ± 1.7	3.5 ± 1.0	0.9 ± 0.3	0.8 ± 0.3	2.3 ± 0.9	2.1 ± 0.6
2015	WI	H	2.0 ± 0.5	1.6 ± 0.0	1.8 ± 0.2	6.8 ± 2.8	6.6 ± 3.1	0.9 ± 0.5	1.1 ± 0.5	3.8 ± 1.5	3.9 ± 1.6
2015	WI	L	1.4 ± 0.4	0.9 ± 0.0	1.1 ± 0.4	4.0 ± 2.3	4.0 ± 2.0	1.1 ± 0.6	1.0 ± 0.4	2.6 ± 1.2	2.5 ± 1.2

Table 23. Continued.

Year	State	Prod.	$VTNT_0$ 0-30	$VTNT_0$ 30-60	$VTNT_0$ 0-60	$PHNT_0$ 0-30	$PHNT_{45}$ 0-30	$PHNT_0$ 30-60	$PHNT_{45}$ 30-60	$PHNT_0$ 0-60	$PHNT_{45}$ 0-60
			------------------ NO_3-N mg kg^{-1} ------------------								
2016	IA	H	0.5 ± 0.3	2.6 ± 4.3	1.6 ± 2.1	5.3 ± 1.7	7.3 ± 3.0	0.6 ± 0.3	1.1 ± 0.6	2.9 ± 0.8	4.2 ± 1.8
2016	IA	L	0.9 ± 0.0	0.5 ± 0.0	0.7 ± 0.1	2.1 ± 0.8	2.3 ± 0.3	0.5 ± 0.0	0.5 ± 0.0	1.3 ± 0.4	1.4 ± 0.1
2016	IL	H	4.3 ± 4.3	4.0 ± 3.5	4.1 ± 3.5	3.9 ± 0.9	3.8 ± 1.6	1.0 ± 0.4	1.4 ± 0.6	2.4 ± 0.6	2.6 ± 0.9
2016	IL	L	7.5 ± 3.5	2.3 ± 1.2	4.9 ± 2.7	2.8 ± 0.3	1.6 ± 0.6	0.5 ± 0.0	0.6 ± 0.3	1.6 ± 0.1	1.1 ± 0.3
2016	IN	H	1.5 ± 2.1	0.6 ± 0.3	1.1 ± 0.3	0.9 ± 0.3	1.0 ± 0.4	0.5 ± 0.0	0.5 ± 0.0	0.7 ± 0.1	0.8 ± 0.2
2016	IN	L	4.5 ± 0.7	1.8 ± 0.9	3.1 ± 1.3	0.9 ± 0.3	0.8 ± 0.3	0.5 ± 0.0	0.5 ± 0.0	0.7 ± 0.1	0.6 ± 0.1
2016	MN	H	0.6 ± 0.3	0.5 ± 0.0	0.6 ± 0.1	1.3 ± 0.3	1.3 ± 0.3	0.5 ± 0.0	0.5 ± 0.0	0.9 ± 0.1	0.9 ± 0.1
2016	MN	L	0.6 ± 0.3	0.6 ± 0.3	0.6 ± 0.3	1.3 ± 0.6	2.4 ± 1.4	0.6 ± 0.3	0.9 ± 0.8	0.9 ± 0.4	1.6 ± 1.1
2016	MO	HB	2.9 ± 0.5	2.3 ± 0.3	1.1 ± 0.8	8.0 ± 0.5	9.0 ± 1.1	2.5 ± 0.6	4.5 ± 1.1	5.3 ± 0.2	6.8 ± 1
2016	MO	HA	1.0 ± 0.7	1.1 ± 0.6	1.9 ± 0.7	5.0 ± 1.6	5.4 ± 0.8	1.1 ± 0.3	1.4 ± 0.3	3.1 ± 0.9	3.4 ± 0.4
2016	MO	L	1.4 ± 1.4	0.9 ± 0.3	1.1 ± 0.3	5.6 ± 2.2	4.0 ± 1.0	0.5 ± 0.0	0.5 ± 0.0	3.1 ± 1.1	2.3 ± 0.5
2016	ND	H	7.5 ± 20.0	2.6 ± 0.9	5.1 ± 1.5	4.3 ± 1.3	3.5 ± 1.7	0.6 ± 0.3	0.8 ± 0.5	2.4 ± 0.6	2.1 ± 1.1
2016	ND	L	16.3 ± 2.4	7.0 ± 7.1	11.6 ± 13.5	5.6 ± 2.8	6.4 ± 2.2	1.4 ± 0.9	1.4 ± 0.8	3.5 ± 1.8	3.9 ± 1.3
2016	NE	H	4.0 ± 0.4	n/a	n/a	2.6 ± 1.4	3.8 ± 1.8	0.5 ± 0.0	0.8 ± 0.5	1.6 ± 0.7	2.3 ± 1
2016	NE	L	3.5 ± 0.6	n/a	n/a	2.0 ± 0.4	2.0 ± 1.4	0.5 ± 0.0	0.6 ± 0.3	1.3 ± 0.2	1.3 ± 0.8
2016	WI	H	6.3 ± 5.0	2.5 ± 0.9	4.4 ± 2.7	0.9 ± 0.3	1.5 ± 1.1	0.5 ± 0.0	0.6 ± 0.3	0.7 ± 0.1	1.1 ± 0.5
2016	WI	L	4.0 ± 0.5	n/a	n/a	3.6 ± 1.9	3.0 ± 0.9	1.9 ± 0.9	2.5 ± 0.0	2.8 ± 1.1	3.1 ± 0.2

† n/a = Soil samples not taken

Table 24. Correlation (r) between plant available water content (retrieved from the SSURGO data base) determined at 0-30 (PAWC0-30), 30-60 (PAWC30-60), and 60-90 cm (PAWC60-90) soil depths and 0-90 cm depth (PAWC0-90: average over 0-30, 30-60, and 60-90 cm depths) with stover dry matter at the 0 (0N), 45 kg N ha^{-1} (45N), and economic optimum N rate (SDM_0, SDM_{45}, and SDM_E), soil texture (clay, silt, and sand content) and residual soil NO_3-N at tasseling at the 0-30, 30-60, and 0-60 cm depth (average over the 0-30 and 30-60 cm depths ($VTNT_0$0-30, $VTNT_0$30-60, and $VTNT_0$0-60, respectively) for eight states in and across three years (2014, 2015, and 2016) and productivity site (high and low based on historical yield data). Plant available water content correlation between the combination of pre-plant residual soil NO_3-N (averaged over 0-30 and 30-60 cm depth) with silt content and mean high temperature two weeks before and after tasseling ($HT_{2wkBAVT}$). Significant correlations ($p \leq 0.10$) with * and bolded.

Plant Available Water Content	All	2014	2015	2016
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	r			
Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**0.30***	**0.37***	**0.39***	**0.22**
Stover Dry Matter at the 0N Rate (SDM_0)	**0.36***	0.29	**0.40***	**0.54***
Stover Dry Matter at the 45N Rate (SDM_{45})	**0.37***	**0.37***	**0.41***	**0.46***
Clay Content	0.06	-0.25	**0.78***	-0.09
Silt Content	**0.55***	**0.36***	**0.87***	**0.47***
Sand Content	**-0.42***	-0.14	**-0.88***	-0.27
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	-0.12	-0.21	**-0.60***	-0.08
Tasseling Soil NO_3-N 30-60 cm at 0N ($VTNT_0$30-60)	-0.06	0.14	0.24	0.00
Tasseling Soil NO_3-N 0-60 cm at 0N ($VTNT_0$0-60)	-0.11	-0.15	0.09	-0.05
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**0.42***	**0.38***	**0.67***	**0.38***
SSURGO Plant Available Water Content at the 30-60 cm depth (PAWC30-60)				
Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**0.31***	-0.05	**0.32***	**0.58***
Stover Dry Matter at the 0N Rate (SDM_0)	**0.24***	0.04	0.28	**0.41***
Stover Dry Matter at the 45N Rate (SDM_{45})	**0.31***	0.15	**0.40***	**0.40***
Clay Content	-0.03	0.21	**0.32***	-0.15
Silt Content	**0.35***	**0.42***	**0.54***	0.10
Sand Content	**-0.23***	-0.21	**-0.49***	0.01
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	-0.13	-0.10	**-0.50***	-0.08
Tasseling Soil NO_3-N 30-60 cm at 0N ($VTNT_0$30-60)	**-0.36***	0.05	0.20	**-0.50***
Tasseling Soil NO_3-N 0-60 cm at 0N ($VTNT_0$0-60)	**-0.24***	0.02	0.13	-0.30
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**0.30***	**0.51***	0.29	**0.36***

Table 24. Continued.

Plant Available Water Content	All	2014	2015	2016
SSURGO Plant Available Water Content at the 60-90 cm depth (PAWC60-90)				
Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**0.32***	0.19	**0.44***	**0.34***
Stover Dry Matter at the 0N Rate (SDM_0)	0.09	0.21	0.22	0.06
Stover Dry Matter at the 45N Rate (SDM_{45})	**0.23***	**0.38***	0.25	0.26
Clay Content	0.06	0.01	**0.35***	-0.00
Silt Content	**0.34***	**0.67***	**0.50***	0.13
Sand Content	**-0.27***	**-0.51***	**-0.47***	-0.09
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	-0.15	-0.03	**-0.58***	-0.01
Tasseling Soil NO_3-N 30-60 cm at 0N ($VTNT_0$30-60)	**-0.46***	**-0.38***	0.12	**-0.51***
Tasseling Soil NO_3-N 0-60 cm at 0N ($VTNT_0$0-60)	**-0.32***	**-0.34***	-0.02	-0.28
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**0.27***	**0.54***	**0.43***	**0.32***
SSURGO Plant Available Water Content 0-90 (averaged over the 0-30, 30-60, and 60-90 cm depth (PAWC0-90)				
Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**0.37***	0.22	**0.42***	**0.46***
Stover Dry Matter at the 0 N Rate (SDM_0)	**0.28***	0.23	**0.32***	**0.36***
Stover Dry Matter at the 45 N Rate (SDM_{45})	**0.37***	**0.38***	**0.38***	**0.43***
Clay Content	0.04	-0.20	**0.52***	-0.09
Silt Content	**0.49***	**0.60***	**0.69***	0.26
Sand Content	**-0.37***	**-0.35***	**-0.66***	-0.14
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	-0.16	-0.15	**-0.61***	-0.06
Tasseling Soil NO_3-N 30-60 cm at 0N ($VTNT_0$30-60)	**-0.36***	-0.19	0.22	**-0.39***
Tasseling Soil NO_3-N 0-60 cm at 0N ($VTNT_0$0-60)	**-0.27***	-0.18	0.08	-0.24
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**0.40***	**0.60***	**0.50***	**0.42***

Table 25. Average (± standard deviation) red reflectance (R), near infrared reflectance (NIR) and normalized difference vegetation index (NDVI = red/near infrared) across all N rates reflectance at the 0 (R_0, NIR_0, and $NDVI_0$) and 45 kg N ha^{-1} treatments) (R_{45}, NIR_{45}, and $NDVI_{45}$) for eight state over a three year period (2014, 2015, and 2016) and two productivity sites (Prod. – high (H) and low (L) based on historical yield data).

Year	State	Prod.	R_0	R_{45}	NIR_0	NIR_{45}	$NDVI_0$	$NDVI_{45}$
2014	IA	H	5.6 ± 0.3	5.1 ± 0.2	38 ± 1	41 ± 1	0.74 ± 0.04	0.78 ± 0.03
2014	IA	L	4.5 ± 0.2	3.7 ± 0.2	40 ± 1	43 ± 1	0.80 ± 0.03	0.84 ± 0.01
2014	IL	H	5.0 ± 0.1	4.4 ± 0.2	37 ± 0	40 ± 1	0.76 ± 0.01	0.80 ± 0.01
2014	IL	L	7.3 ± 0.3	6.9 ± 0.6	34 ± 1	36 ± 2	0.65 ± 0.04	0.68 ± 0.07
2014	IN	H	4.3 ± 0.1	4.0 ± 0.1	41 ± 1	43 ± 0	0.81 ± 0.00	0.83 ± 0.01
2014	IN	L	4.8 ± 0.1	4.5 ± 0.1	41 ± 0	42 ± 1	0.79 ± 0.01	0.81 ± 0.01
2014	MN	H	6.2 ± 0.3	4.7 ± 0.4	35 ± 1	37 ± 2	0.70 ± 0.09	0.77 ± 0.03
2014	MN	L	4.2 ± 0.4	3.9 ± 0.1	39 ± 2	43 ± 1	0.81 ± 0.02	0.83 ± 0.00
2014	MO	H	4.4 ± 0.1	4.1 ± 0.1	41 ± 0	43 ± 1	0.80 ± 0.01	0.83 ± 0.00
2014	MO	L	4.6 ± 0.4	4.2 ± 0.2	40 ± 2	44 ± 2	0.79 ± 0.03	0.82 ± 0.02
2014	ND†	H	0.1 ± 0.0	0.1 ± 0.0	0 ± 0†	0 ± 0	0.47 ± 0.06	0.60 ± 0.04
2014	ND	L	0.2 ± 0.1	0.2 ± 0.0	0 ± 0	1 ± 0	0.37 ± 0.06	0.52 ± 0.04
2014	NE	H	4.1 ± 0.1	3.8 ± 0.1	46 ± 0	47 ± 1	0.84 ± 0.01	0.85 ± 0.01
2014	NE	L	7.1 ± 0.5	6.2 ± 0.5	36 ± 2	38 ± 2	0.67 ± 0.07	0.72 ± 0.06
2014	WI	H	4.8 ± 0.1	4.2 ± 0.0	38 ± 0	40 ± 0	0.78 ± 0.01	0.81 ± 0.00
2014	WI	L	5.9 ± 0.2	5.1 ± 0.1	37 ± 1	39 ± 1	0.73 ± 0.04	0.77 ± 0.02
2015	IA	H	7.7 ± 0.4	6.2 ± 0.2	37 ± 2	41 ± 1	0.66 ± 0.06	0.74 ± 0.03
2015	IA	L	4.5 ± 0.2	3.9 ± 0.2	38 ± 1	42 ± 1	0.79 ± 0.02	0.83 ± 0.01
2015	IL	H	4.6 ± 0.2	4.4 ± 0.2	40 ± 1	41 ± 1	0.79 ± 0.03	0.81 ± 0.02
2015	IL	L	4.6 ± 0.1	3.8 ± 0.1	35 ± 1	39 ± 1	0.77 ± 0.01	0.82 ± 0.01
2015	IN	H	4.4 ± 0.3	4.0 ± 0.1	40 ± 2	42 ± 0	0.80 ± 0.03	0.83 ± 0.01
2015	IN	L	5.6 ± 0.3	5.1 ± 0.2	39 ± 1	41 ± 1	0.75 ± 0.03	0.78 ± 0.02
2015	MN	H	5.9 ± 0.3	4.5 ± 0.2	37 ± 1	40 ± 1	0.72 ± 0.04	0.80 ± 0.02
2015	MN	L	3.8 ± 0.2	3.7 ± 0.1	40 ± 1	42 ± 0	0.83 ± 0.02	0.84 ± 0.01
2015	MO	H	4.3 ± 0.1	4.0 ± 0.0	38 ± 1	42 ± 0	0.80 ± 0.01	0.83 ± 0.01
2015	MO	L	5.2 ± 0.3	5.5 ± 0.3	33 ± 1	33 ± 1	0.73 ± 0.03	0.71 ± 0.06
2015	ND‡	H	14.7 ± 0.2	14.1 ± 0.2	30 ± 0	30 ± 1	0.34 ± 0.02	0.37 ± 0.02
2015	ND	L	16.8 ± 0.2	15.5 ± 0.7	29 ± 1	29 ± 2	0.26 ± 0.02	0.31 ± 0.07
2015	NE	H	5.4 ± 0.0	5.0 ± 0.1	42 ± 0	43 ± 1	0.77 ± 0.02	0.79 ± 0.02
2015	NE	L	7.0 ± 0.1	6.4 ± 0.1	33 ± 0	34 ± 1	0.65 ± 0.02	0.68 ± 0.00
2015	WI	H	4.1 ± 0.1	4.0 ± 0.1	40 ± 0	42 ± 1	0.81 ± 0.01	0.83 ± 0.00
2015	WI	L	3.9 ± 0.0	3.7 ± 0.1	38 ± 0	41 ± 1	0.81 ± 0.02	0.83 ± 0.01

Table 25. Continued.

Year	State	Prod.	R_0	R_{45}	NIR_0	NIR_{45}	$NDVI_0$	$NDVI_{45}$
2016	IA	H	4.3 ± 0.2	4.2 ± 0.2	41 ± 1	43 ± 1	0.81 ± 0.01	0.82 ± 0.01
2016	IA	L	4.6 ± 0.1	4.7 ± 0.2	41 ± 1	43 ± 1	0.80 ± 0.01	0.80 ± 0.02
2016	IL	H	6.9 ± 0.2	6.6 ± 0.2	38 ± 1	39 ± 1	0.69 ± 0.03	0.71 ± 0.03
2016	IL	L	9.3 ± 0.2	9.1 ± 0.3	34 ± 1	35 ± 1	0.57 ± 0.04	0.59 ± 0.05
2016	IN	H	4.5 ± 0.2	4.3 ± 0.1	40 ± 1	42 ± 1	0.80 ± 0.02	0.81 ± 0.02
2016	IN	L	5.4 ± 0.2	5.3 ± 0.2	39 ± 1	42 ± 1	0.76 ± 0.03	0.77 ± 0.03
2016	MN	H	5.3 ± 0.1	4.4 ± 0.4	36 ± 1	39 ± 2	0.75 ± 0.02	0.80 ± 0.02
2016	MN	L	4.6 ± 0.2	4.4 ± 0.2	38 ± 1	41 ± 1	0.78 ± 0.02	0.81 ± 0.01
2016	MO	HA	4.9 ± 0.3	3.7 ± 0.1	38 ± 2	41 ± 1	0.77 ± 0.03	0.84 ± 0.01
2016	MO	HB	6.6 ± 0.1	4.8 ± 0.1	35 ± 1	39 ± 0	0.68 ± 0.02	0.78 ± 0.01
2016	MO	L	6.2 ± 0.2	5.6 ± 0.0	38 ± 1	41 ± 0	0.72 ± 0.04	0.76 ± 0.01
2016	ND	H	14.2 ± 0.1	13.5 ± 0.3	30 ± 0	31 ± 1	0.36 ± 0.03	0.39 ± 0.04
2016	ND	L	8.6 ± 0.3	8.2 ± 0.4	34 ± 1	34 ± 1	0.60 ± 0.04	0.62 ± 0.06
2016	NE	H	7.5 ± 0.1	6.3 ± 0.2	40 ± 1	43 ± 1	0.68 ± 0.01	0.75 ± 0.02
2016	NE	L	5.0 ± 0.0	4.4 ± 0.1	40 ± 0	44 ± 1	0.78 ± 0.03	0.82 ± 0.01
2016	WI	H	4.2 ± 0.1	4.4 ± 0.1	40 ± 1	40 ± 1	0.81 ± 0.01	0.80 ± 0.01
2016	WI	L	4.3 ± 0.2	4.3 ± 0.2	41 ± 1	42 ± 1	0.81 ± 0.02	0.81 ± 0.02

† Crop reflectance taken with Crop Circle 430 in 2014 at ND.

‡ Crop reflectance taken at V5 and V6 for low and high site, respectively.

Table 26. Correlation (r) between crop reflectance variables at the 0 (0N) and 45 kg N ha^{-1} (45N) with internal N efficiency at the economic optimum N rate (IE_E) for eight states in and across three years (2014, 2015, and 2016), two productivity sites (high and low based on historical yield data), and N application timings (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage). Significant correlations ($p \leq 0.10$) with * and bolded.

Crop Reflectance	All	2014	2015	2016
Red Reflectance (RE)	r			
Red reflectance at 0N (R_0)	0.16	**0.41***	0.23	0.07
Red reflectance at 45N (R_{45})	0.16	0.28	0.18	0.12
Near Infrared Reflectance (NIR)				
Near Infrared reflectance at 0N (NIR_0)	-0.13	-0.24	**-0.49***	0.11
Near Infrared reflectance at 45N (NIR_{45})	-0.16	**-0.40***	**-0.40***	0.10
Normalized Difference Vegetation Index (NDVI)†				
Normalized difference vegetation index at 0N ($NDVI_0$)	-0.18	**-0.47***	**-0.34***	-0.03
Normalized difference vegetation index at 45N ($NDVI_{45}$)	-0.17	**-0.36***	-0.27	-0.08
NDVI Sufficiency Indices‡				
NDVI at 0N / NDVI at 225N ($NDVI_0225$)	**-0.26***	**-0.47***	**-0.48***	-0.07
NDVI at 45N / NDVI at 225N ($NDVI_{45}225$)	**-0.30***	-0.32	**-0.39***	-0.28
NDVI at 0N / NDVI at 270N ($NDVI_0270$)	**-0.23***	**-0.47***	**-0.50***	-0.04
NDVI at 45N / NDVI at 270N ($NDVI_{45}270$)	**-0.23***	-0.24	**-0.33***	-0.19
NDVI Simple Ratio (SI)§				
Simple Ratio Index at 0N (SI_{R0})	**-0.22***	**-0.45***	**-0.51***	-0.06
Simple Ratio Index at 45N (SI_{R45})	**-0.32***	-0.29	**-0.41***	**-0.34***
Red Edge Reflectance (RE)				
Red Edge at 0N (RE_0)	**0.20***	**0.60***	**0.48***	-0.10
Red Edge at 45N (RE_{45})	0.17	**0.54***	**0.37***	-0.08
Normalized Difference Red Edge Reflectance (NDRE)¶				
Normalized difference red edge at 0N ($NDRE_0$)	**-0.21***	**-0.60***	**-0.48***	0.10
Normalized difference red edge at 45N ($NDRE_{45}$)	**-0.18***	**-0.55***	**-0.38***	0.08

Table 26. Continued.

	All	2014	2015	2016
NDRE Sufficiency Indices#	r			
NDRE at 0N / NDRE at 225N ($NDRE_0225$)	**-0.27***	**-0.52***	**-0.44**	-0.12
NDRE at 45N / NDRE at 225N ($NDRE_{45}225$)	**-0.29***	**-0.44***	**-0.35***	-0.23
NDRE 0N/270N ($NDRE_0270$)	**-0.25***	**-0.54***	**-0.43***	-0.09
NDRE 45N/270N ($NDRE_{45}270$)	**-0.26***	**-0.46***	**-0.33***	-0.19
NDRE Simple Ratio (SI)††				
Simple Ratio Index at 0N (SI_{RE0})	**-0.24***	**-0.44***	**-0.40***	-0.14
Simple Ratio Index at 45N (SI_{RE45})	**-0.27***	-0.25	**-0.35***	-0.23

† NDVI = red/near infrared.

‡ $NDVI_0225$ and $NDVI_{45}225$ = [NDVI at 0 or 45N (red at 0 or 45N/near infrared at 0 or 45N)/NDVI at 225N (red at 225N/near infrared at 225N)] and $NDVI_0270$ and $NDVI_{45}270$ = [NDVI at 0 or 45N (red at 0 or 45N/near infrared at 0 or 45N)/NDVI at 270N (red at 270N/near infrared at 270N)].

§ SI_{R0} = (red at 0N/near infrared at 0N) and SI_{R45} = red at 45N/near infrared at 45N).

¶ NDRE = red edge/near infrared.

$NDRE_0225$ and $NDRE_{45}225$ = [NDRE at 0 or 45N (red edge at 0 or 45N/near infrared at 0 or 45N)/NDRE at 225N (red edge at 225N/near infrared at 225N)] and $NDRE_0270$ and $NDRE_{45}270$ = [NDRE at 0 or 45N (red edge at 0 or 45N/near infrared at 0 or 45N)/NDRE at 270N (red edge at 270N/near infrared at 270N)].

†† SI_{RE0} = (red edge at 0N/near infrared at 0N) and SI_{RE45} = (red edge at 45N/near infrared at 45N).

Table 27. Average (± standard deviation) red edge (RE) and normalized difference red edge (NDRE = red edge/near infrared) reflectance from 0 (RE_0 and $NDRE_0$) and 45 kg N ha^{-1} treatments (RE_{45} and $NDRE_{45}$) for eight state over a three year period (2014, 2015, and 2016) and two productivity sites (Prod. - high (H) and low (L) based on historical yield data).

Year	State	Prod.	RE_0	RE_{45}	$NDRE_0$	$NDRE_{45}$
2014	IA	H	19.6 ± 0.3	18.9 ± 0.2	0.32 ± 0.02	0.37 ± 0.02
2014	IA	L	19.2 ± 0.2	18.7 ± 0.2	0.35 ± 0.02	0.39 ± 0.01
2014	IL	H	19.6 ± 0.1	19.1 ± 0.2	0.31 ± 0.00	0.36 ± 0.01
2014	IL	L	20.3 ± 0.3	20.0 ± 0.6	0.26 ± 0.02	0.28 ± 0.04
2014	IN	H	18.9 ± 0.1	18.6 ± 0.1	0.37 ± 0.01	0.40 ± 0.01
2014	IN	L	19.0 ± 0.1	18.8 ± 0.1	0.36 ± 0.01	0.38 ± 0.01
2014	MN	H	20.3 ± 0.3	19.7 ± 0.4	0.26 ± 0.02	0.31 ± 0.03
2014	MN	L	19.3 ± 0.4	18.7 ± 0.1	0.34 ± 0.04	0.39 ± 0.01
2014	MO	H	19.0 ± 0.1	18.6 ± 0.1	0.36 ± 0.01	0.40 ± 0.01
2014	MO	L	19.1 ± 0.4	18.5 ± 0.2	0.36 ± 0.03	0.40 ± 0.02
2014†	ND	H	0.2 ± 0.0	0.2 ± 0.0	0.22 ± 0.03	0.31 ± 0.02
2014	ND	L	0.3 ± 0.1	0.3 ± 0.0	0.16 ± 0.02	0.23 ± 0.02
2014	NE	H	18.3 ± 0.1	18.2 ± 0.1	0.43 ± 0.00	0.44 ± 0.01
2014	NE	L	20.0 ± 0.5	19.6 ± 0.5	0.28 ± 0.04	0.31 ± 0.04
2014	WI	H	19.4 ± 0.1	19.0 ± 0.0	0.33 ± 0.01	0.36 ± 0.00
2014	WI	L	19.6 ± 0.2	19.3 ± 0.1	0.31 ± 0.02	0.34 ± 0.01
2015	IA	H	19.7 ± 0.4	19.0 ± 0.2	0.31 ± 0.03	0.37 ± 0.02
2015	IA	L	19.5 ± 0.2	18.8 ± 0.2	0.32 ± 0.02	0.38 ± 0.02
2015	IL	H	19.2 ± 0.2	19.0 ± 0.2	0.35 ± 0.01	0.37 ± 0.01
2015	IL	L	20.1 ± 0.1	19.2 ± 0.1	0.28 ± 0.01	0.34 ± 0.01
2015	IN	H	19.2 ± 0.3	18.8 ± 0.1	0.35 ± 0.03	0.38 ± 0.01
2015	IN	L	19.3 ± 0.3	19.0 ± 0.2	0.34 ± 0.02	0.37 ± 0.02
2015	MN	H	19.8 ± 0.3	19.1 ± 0.2	0.30 ± 0.02	0.36 ± 0.02
2015	MN	L	19.0 ± 0.2	18.8 ± 0.1	0.36 ± 0.02	0.38 ± 0.01
2015	MO	H	19.6 ± 0.1	18.8 ± 0.0	0.32 ± 0.01	0.38 ± 0.00
2015	MO	L	20.7 ± 0.3	20.7 ± 0.3	0.23 ± 0.02	0.23 ± 0.02
2015‡	ND	H	21.8 ± 0.2	21.6 ± 0.2	0.16 ± 0.01	0.17 ± 0.02
2015	ND	L	22.4 ± 0.2	22.2 ± 0.7	0.12 ± 0.01	0.14 ± 0.05
2015	NE	H	18.8 ± 0.0	18.6 ± 0.1	0.39 ± 0.00	0.40 ± 0.01
2015	NE	L	20.6 ± 0.1	20.4 ± 0.1	0.24 ± 0.01	0.25 ± 0.01
2015	WI	H	19.1 ± 0.1	18.9 ± 0.1	0.36 ± 0.01	0.37 ± 0.01
2015	WI	L	19.4 ± 0.0	19.0 ± 0.1	0.33 ± 0.00	0.36 ± 0.01

Table 27. Continued.

Year	State	Prod.	RE_0	RE_{45}	$NDRE_0$	$NDRE_{45}$
2016	IA	H	19.0 ± 0.2	18.6 ± 0.2	0.36 ± 0.02	0.40 ± 0.02
2016	IA	L	19.0 ± 0.1	18.7 ± 0.2	0.37 ± 0.01	0.39 ± 0.01
2016	IL	H	19.5 ± 0.2	19.2 ± 0.2	0.32 ± 0.01	0.34 ± 0.02
2016	IL	L	20.4 ± 0.2	20.2 ± 0.3	0.25 ± 0.02	0.27 ± 0.02
2016	IN	H	19.1 ± 0.2	18.9 ± 0.1	0.36 ± 0.02	0.37 ± 0.01
2016	IN	L	19.3 ± 0.2	18.9 ± 0.2	0.34 ± 0.01	0.38 ± 0.02
2016	MN	H	19.9 ± 0.1	19.3 ± 0.4	0.29 ± 0.01	0.34 ± 0.03
2016	MN	L	19.5 ± 0.2	19.0 ± 0.2	0.32 ± 0.01	0.37 ± 0.01
2016	MO	HA	19.4 ± 0.3	18.9 ± 0.1	0.33 ± 0.03	0.37 ± 0.01
2016	MO	HB	20.2 ± 0.1	19.4 ± 0.1	0.26 ± 0.01	0.33 ± 0.01
2016	MO	L	19.5 ± 0.2	19.1 ± 0.0	0.33 ± 0.01	0.36 ± 0.00
2016	ND	H	21.6 ± 0.1	21.5 ± 0.3	0.17 ± 0.01	0.18 ± 0.02
2016	ND	L	20.4 ± 0.3	20.4 ± 0.4	0.25 ± 0.02	0.26 ± 0.03
2016	NE	H	19.2 ± 0.1	18.6 ± 0.2	0.35 ± 0.01	0.40 ± 0.02
2016	NE	L	19.1 ± 0.0	18.5 ± 0.1	0.35 ± 0.00	0.40 ± 0.01
2016	WI	H	19.1 ± 0.1	19.1 ± 0.1	0.36 ± 0.01	0.35 ± 0.01
2016	WI	L	18.9 ± 0.2	18.8 ± 0.2	0.37 ± 0.02	0.38 ± 0.01

† Crop reflectance taken with Crop Circle 430 in 2014 at ND.

‡ Crop reflectance taken at V5 and V6 for low and high site, respectively.

Table 28. Average sufficiency indices of the normalized difference vegetation index and simple ratio at the 0 (ISR0 = red at 0N/near infrared at 0N) and 45 kg N ha-1 treatments (SIR45 = red at 45N/near infrared at 45N) as target values and N rates 225 kg N ha-1 (NDVI0225 and NDVI45225) = [NDVI at 0 or 45N (red at 0 or 45N/near infrared at 0 or 45N)/NDVI at 225N (red at 225N/near infrared at 225N)] and 270 kg N ha-1 (NDVI0270 and NDVI45270) = [NDVI at 0 or 45N (red at 0 or 45N/near infrared at 0 or 45N)/NDVI at 270N (red at 270N/near infrared at 270N)] as the N rich values for eight state over a three year period (2014, 2015, and 2016) and two productivity sites (Prod. – high (H) and low (L) based on historical yield data).

Year	State	Prod.	$NDVI_0$225	$NDVI_{45}$225	$NDVI_0$270	$NDVI_{45}$270	SI_{R0}	SI_{R45}
2014	IA	H	0.92	0.97	0.92	0.96	1.38	1.16
2014	IA	L	0.94	0.99	0.94	0.99	1.36	1.04
2014	IL	H	0.94	0.99	0.94	0.99	1.29	1.05
2014	IL	L	0.88	0.91	0.90	0.93	1.38	1.26
2014	IN	H	0.99	1.01	0.97	1.00	1.11	0.98
2014	IN	L	0.98	1.01	0.95	0.98	1.15	1.04
2014	MN	H	0.87	0.97	0.89	0.99	1.57	1.11
2014	MN	L	0.95	0.98	0.95	0.99	1.28	1.09
2014	MO	H	0.96	0.99	0.98	1.00	1.16	1.02
2014	MO	L	0.94	0.98	0.94	0.98	1.33	1.11
2014	ND	H	†	.	.	.	.	.
2014	ND	L	.	.	.	.	.	.
2014	NE	H	0.99	1.01	1.00	1.02	1.02	0.93
2014	NE	L	0.82	0.88	0.85	0.91	1.76	1.17
2014	WI	H	0.94	0.98	0.93	0.97	1.33	1.11
2014	WI	L	0.92	0.98	0.91	0.97	1.36	1.12
2015	IA	H	0.88	0.99	0.92	1.03	1.32	0.98
2015	IA	L	0.93	0.98	0.93	0.98	1.44	1.12
2015	IL	H	0.98	0.99	0.97	0.99	1.13	1.04
2015	IL	L	0.90	0.97	0.90	0.96	1.66	1.23
2015	IN	H	0.96	0.99	0.96	1.00	1.21	1.02
2015	IN	L	0.95	0.99	0.97	1.01	1.16	1.02
2015	MN	H	0.88	0.97	0.88	0.98	1.61	1.12
2015	MN	L	0.96	0.98	0.97	0.98	1.20	1.12
2015	MO	H	0.94	0.97	0.94	0.98	1.39	1.16
2015	MO	L	0.88	0.87	0.87	0.86	1.70	1.78
2015	ND	H	‡	.	.	.	.	.
2015	ND	L	.	.	.	.	.	.
2015	NE	H	0.96	0.99	0.96	0.98	1.18	1.07
2015	NE	L	0.85	0.89	0.85	0.89	1.61	1.44
2015	WI	H	0.98	0.99	0.99	1.00	1.09	1.02
2015	WI	L	1.05	1.07	0.96	0.99	0.98	0.87

Table 28. Continued.

Year	State	Prod.	$NDVI_0225$	$NDVI_{45}225$	$NDVI_0270$	$NDVI_{45}270$	SI_{R0}	SI_{R45}
2016	IA	H	0.96	0.98	0.97	0.99	1.19	1.10
2016	IA	L	0.98	0.99	0.98	0.99	1.10	1.07
2016	IL	H	0.96	0.98	0.96	0.98	1.14	1.06
2016	IL	L	0.84	0.87	0.82	0.85	1.46	1.39
2016	IN	H	0.96	0.98	0.97	0.98	1.20	1.12
2016	IN	L	0.97	0.99	0.95	0.97	1.17	1.08
2016	MN	H	0.89	0.96	0.90	0.97	1.56	1.21
2016	MN	L	0.94	0.96	0.94	0.97	1.35	1.19
2016	MO	HA	0.92	0.99	0.92	1.00	1.49	1.05
2016	MO	HB	0.88	1.00	0.86	0.98	1.56	1.02
2016	MO	L	0.95	1.00	0.96	1.02	1.17	0.98
2016	ND	H	0.93	0.99	1.01	1.08	1.03	0.97
2016	ND	L	0.97	0.99	0.98	1.00	1.06	1.00
2016	NE	H	0.94	0.98	0.95	1.00	1.29	1.04
2016	NE	L	0.89	0.97	0.88	0.97	1.46	1.12
2016	WI	H	1.07	1.06	1.04	1.03	0.81	0.84
2016	WI	L	1.03	1.03	0.99	0.99	0.95	0.95

† Crop reflectance taken with Crop Circle 430 in 2014 at ND.

‡ Crop reflectance taken at V5 and V6 for low and high site, respectively.

Table 29. Average sufficiency indices of the normalized different red edge and simple ratio at the 0 (SI_{RE0} = red edge at 0N/near infrared at 0N) and 45 kg N ha^{-1} treatments (SI_{RE45} = red edge at 45N/near infrared at 45N) as target values and N rates 225 kg N ha^{-1} (($NDRE_0$225 and $NDRE_{45}$225) = [NDRE at 0 or 45N (red edge at 0 or 45N/near infrared at 0 or 45N)/ NDRE at 225N (red edge at 225N/near infrared at 225N)] and 270 kg N ha^{-1} ($NDRE_0$270 and $NDRE_{45}$270) = [NDRE at 0 or 45N (red edge at 0 or 45N/near infrared at 0 or 45N)/NDRE at 270N (red edge at 270N/near infrared at 270N)] as the N rich values for eight state over a three year period and two productivity sites (Prod. – high (H) and low (L) based on historical yield data).

Year	State	Prod.	$NDRE_0$ 225	$NDRE_0$ 270	$NDRE_{45}$ 225	$NDRE_{45}$ 270	SI_{RE0}	SI_{RE45}
2014	IA	H	0.81	0.81	0.95	0.94	1.19	1.05
2014	IA	L	0.86	0.85	0.96	0.96	1.15	1.04
2014	IL	H	0.84	0.84	0.95	0.96	1.14	1.04
2014	IL	L	0.78	0.81	0.85	0.88	1.16	1.10
2014	IN	H	0.93	0.92	1.00	0.98	1.07	1.01
2014	IN	L	0.94	0.90	0.98	0.94	1.08	1.04
2014	MN	H	0.72	0.72	0.85	0.85	1.26	1.14
2014	MN	L	0.81	0.81	0.93	0.93	1.20	1.07
2014	MO	H	0.88	0.89	0.97	0.98	1.12	1.03
2014	MO	L	0.83	0.83	0.94	0.94	1.19	1.06
2014	ND	H	†	.	.	.	.	.
2014	ND	L	.	.	.	.	.	.
2014	NE	H	0.97	0.98	0.99	1.00	1.03	1.00
2014	NE	L	0.70	0.73	0.79	0.81	1.29	0.96
2014	WI	H	0.88	0.87	0.96	0.95	1.11	1.04
2014	WI	L	0.86	0.86	0.95	0.95	1.12	1.05
2015	IA	H	0.79	0.82	0.94	0.97	1.19	1.04
2015	IA	L	0.76	0.76	0.91	0.91	1.26	1.09
2015	IL	H	0.92	0.90	0.97	0.95	1.08	1.04
2015	IL	L	0.70	0.69	0.87	0.86	1.32	1.14
2015	IN	H	0.92	0.93	1.02	1.03	1.07	0.98
2015	IN	L	0.89	0.91	0.95	0.98	1.09	1.03
2015	MN	H	0.78	0.79	0.93	0.95	1.21	1.06
2015	MN	L	0.87	0.88	0.92	0.93	1.13	1.07
2015	MO	H	0.75	0.76	0.90	0.92	1.27	1.10
2015	MO	L	0.67	0.64	0.67	0.64	1.30	1.30
2015	ND	H	‡	.	.	.	.	.
2015	ND	L	.	.	.	.	.	.
2015	NE	H	0.94	0.93	0.97	0.96	1.07	1.03
2015	NE	L	0.69	0.68	0.74	0.73	1.27	1.23
2015	WI	H	0.92	0.92	0.96	0.96	1.08	1.03
2015	WI	L	0.90	0.84	1.00	0.93	1.12	1.03

Table 29. Continued.

Year	State	Prod.	$NDRE_0$ 225	$NDRE_0$ 270	$NDRE_{45}$ 225	$NDRE_{45}$ 270	SI_{RE0}	SI_{RE45}
2016	IA	H	0.81	0.82	0.88	0.89	1.22	1.13
2016	IA	L	0.85	0.86	0.91	0.92	1.16	1.09
2016	IL	H	0.91	0.93	0.97	0.99	1.07	1.02
2016	IL	L	0.75	0.74	0.80	0.79	1.21	1.17
2016	IN	H	0.86	0.86	0.90	0.91	1.14	1.10
2016	IN	L	0.85	0.83	0.94	0.91	1.17	1.07
2016	MN	H	0.76	0.78	0.89	0.90	1.22	1.09
2016	MN	L	0.77	0.77	0.88	0.87	1.25	1.13
2016	MO	HA	0.82	0.83	0.93	0.93	1.18	1.07
2016	MO	HB	0.81	0.78	1.02	0.98	1.16	1.00
2016	MO	L	0.85	0.87	0.95	0.98	1.13	1.03
2016	ND	H	0.94	1.01	0.99	1.06	1.01	0.99
2016	ND	L	0.97	0.98	0.98	0.99	1.01	1.01
2016	NE	H	0.81	0.80	0.93	0.92	1.22	1.08
2016	NE	L	0.81	0.83	0.93	0.94	1.20	1.07
2016	WI	H	1.17	1.15	1.15	1.14	0.90	0.90
2016	WI	L	1.04	0.99	1.07	1.02	0.99	0.96

† Crop reflectance taken with Crop Circle 430 in 2014 at ND.

‡ Crop reflectance taken at V5 and V6 for low and high site, respectively.

Table 30. Correlation (r) between sufficiency indices of normalized difference vegetative index and simple ratios at two N treatments (non-fertilized (0N) and 45 kg N ha^{-1} (45N)) with components of internal N efficiency at the economic optimum N rate and soil NO_3-N variables at eight states in and across three years (2014, 2015, and 2016) and two productivity sites (high and low based on historical yield data). Significant correlations ($p \leq 0.10$) with * and bolded.

Sufficiency Indices of Normalized Difference Vegetative Index†	All	2014	2015	2016
Normalized Difference Vegetative Index Target (0N) / NDVI at the 225 kg N ha^{-1} ($NDVI_0225$)	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.13	0.29	0.25	-0.06
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.47***	**0.37***	**0.75***	**0.36***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.21***	**0.41***	**0.44***	-0.06
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.09	**0.56***	0.05	-0.15
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.05	0.17	0.31	-0.16
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.33***	**0.48***	**0.44***	0.14
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_00$-30)	**0.46***	**0.52***	0.27	**0.56***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}0$-30)	**0.51***	**0.48***	**0.38***	**0.62***
Normalized Difference Vegetative Index Target (0N) / NDVI at the 270 kg N ha^{-1} ($NDVI_0270$)				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.11	**0.34***	0.29	-0.15
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.40***	**0.37***	**0.68***	0.27
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.19***	**0.46***	**0.47***	-0.11
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.12	**0.57***	0.20	-0.10
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	-0.01	0.23	0.28	-0.26
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.42***	**0.49***	**0.40***	**0.38***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_00$-30)	**0.51***	**0.53***	**0.35***	**0.57***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}0$-30)	**0.56***	**0.49***	**0.54***	**0.58***

Table 30. Continued.

	All	2014	2015	2016
Normalized Difference Vegetative Index Target (45N) / NDVI at the 225 kg N ha^{-1} ($NDVI_{45}225$)				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.15	0.09	**0.33***	-0.02
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.43***	0.21	**0.70***	**0.35***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.26***	0.21	**0.41***	0.18
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.17	**0.42***	0.11	0.08
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.15	0.10	0.15	0.14
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.31***	**0.38***	**0.40***	0.18
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_0$0-30)	**0.40***	**0.49***	0.16	**0.57***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}$0-30)	**0.50***	**0.51***	**0.38***	**0.62***
Normalized Difference Vegetative Index Target (45N) / NDVI at the 270 kg N ha^{-1} ($NDVI_{45}270$)				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.11	0.09	**0.35***	-0.14
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.29***	0.15	**0.52***	0.18
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.21***	0.15	**0.38***	0.07
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**0.19***	0.21	0.25	0.13
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.06	**0.35***	0.07	-0.01
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.38***	**0.34***	0.30	**0.44***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_0$0-30)	**0.40***	**0.47***	0.19	**0.49***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}$0-30)	**0.50***	**0.51***	**0.49***	**0.49***

Table 30. Continued.

Simple Ratio Sufficiency Index of Red Reflectance‡	All	2014	2015	2016
Simple Ratio Sufficiency Index of Red Reflectance at the 0N (SI_{R0})	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.09	**0.39***	0.30	-0.27
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.51***	**0.46***	**0.72***	**0.44***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	0.15	**0.48***	**0.49***	-0.22
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	-0.06	**0.49***	-0.02	**-0.30***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.04	0.22	**0.43***	-0.26
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.54***	**0.63***	**0.57***	**0.48***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_0$0-30)	**0.64***	**0.64***	**0.34***	**0.79***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}$0-30)	**0.61***	**0.51***	**0.45***	**0.73***
Simple Ratio Sufficiency Index of Red Reflectance at the 45N (SI_{R45})				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	**0.21***	**0.49***	**0.33***	-0.14
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.50***	**0.35***	**0.65***	**0.46***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.32***	**0.47***	**0.41***	0.14
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.10	**0.38***	0.08	-0.00
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**0.21***	0.31	0.22	0.17
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.46***	**0.63***	**0.44***	**0.43***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_0$0-30)	**0.50***	**0.61***	0.17	**0.78***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}$0-30)	**0.54***	**0.44***	**0.40***	**0.74***

† $NDVI_0$225 and $NDVI_0$270 = [NDVI at 0N (red at 0N/near infrared at 0N)/NDVI at 225 or 270N (red at 225 or 270N/near infrared at 225 or 270N)] and $NDVI_{45}$225 and $NDVI_{45}$270 = [NDVI at 45N (red at 45N/near infrared at 45N)/NDVI at 225 or 270N (red at 225 or 270N/near infrared at 225 or 270N)].

‡ SI_{R0} = (red at 0N/near infrared at 0N) and SI_{R45} = red at 45N/near infrared at 45N).

Table 31. Correlation (r) between normalized difference red edge indices at two N treatments (non-fertilized (0N) and 45 kg N ha^{-1} (45N)) with components of internal N efficiency at the economic optimum N rate and soil NO_3-N variables at eight states in and across three years (2014, 2015, and 2016) and two productivity sites (high and low based on historical yield data). Significant correlations ($p \leq 0.10$) with * and bolded.

Sufficiency Indices of Normalized Difference Red Edge Index †	All	2014	2015	2016
Normalized Difference Red Edge Index Target (0N) / NDRE at the 225 kg N ha^{-1} ($NDRE_0225$)	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.14	**0.44***	**0.41***	**-0.30***
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.54***	**0.43***	**0.69***	**0.51***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.22***	**0.50***	**0.51***	-0.15
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	-0.01	**0.58***	-0.00	**-0.30***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.09	0.24	**0.37***	-0.15
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.56***	**0.64***	**0.62***	**0.48***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_00$-30)	**0.72***	**0.61***	**0.55***	**0.85***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}0$-30)	**0.71***	**0.43***	**0.66***	**0.84***
Normalized Difference Red Edge Index Target (0 N) / NDRE at the 270 kg N ha^{-1} ($NDRE_0270$)				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.13	**0.51***	**0.42***	**-0.34***
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.52***	**0.47***	**0.63***	**0.48***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.21***	**0.56***	**0.51***	-0.19
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.00	**0.61***	0.05	**-0.30***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.05	0.26	**0.34***	-0.21
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.59***	**0.66***	**0.56***	**0.59***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_00$-30)	**0.72***	**0.61***	**0.54***	**0.79***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}0$-30)	**0.72***	**0.41***	**0.69***	**0.84***

Table 31. Continued.

	All	2014	2015	2016
Normalized Difference Red Edge Index Target (45N) / NDRE at the 225 kg N ha^{-1} ($NDRE_{45}225$)	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.17	0.26	**0.37***	-0.18
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.47***	0.23	**0.64***	**0.45***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.26***	**0.35***	**0.40***	0.04
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.12	**0.58***	0.10	-0.11
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.13	0.16	0.13	0.08
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.38***	**0.40***	**0.42***	**0.34***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_0$0-30)	**0.53***	**0.45***	0.29	**0.76***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}$0-30)	**0.61***	**0.46***	**0.53***	**0.75***
Normalized Difference Red Edge Index Target (45N) / NDRE at the 270 kg N ha^{-1} ($NDRE_{45}270$)				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.15	**0.33***	**0.36***	-0.24
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.43***	0.25	**0.56***	**0.40***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.24***	**0.42***	**0.38***	-0.01
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.12	**0.63***	0.15	-0.11
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.08	0.18	0.11	-0.00
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.41***	**0.39***	**0.35***	**0.51***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_0$0-30)	**0.52***	**0.44***	0.27	**0.86***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}$0-30)	**0.62***	**0.45***	**0.54***	**0.78***

Table 31. Continued.

Simple Ratio Sufficiency Index of Red Edge Reflectance‡	All	2014	2015	2016
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 0N (SI_{RE0})	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.04	**0.43***	**0.37***	**-0.42***
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.55***	**0.42***	**0.60***	**0.57***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	0.14	**0.45***	**0.46***	-0.20
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	-0.08	**0.49***	-0.07	**-0.32***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.03	0.17	**0.39***	-0.20
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.61***	**0.67***	**0.62***	**0.60***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_0$0-30)	**0.76***	**0.67***	**0.57***	**0.88***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}$0-30)	**0.74***	**0.43***	**0.65***	**0.87***
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 45N (SI_{RE45})				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	**0.18***	**0.84***	**0.33***	-0.28
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.50***	0.27	**0.58***	**0.50***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.26***	**0.61***	**0.37***	-0.02
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.03	**0.32***	0.07	-0.17
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.13	**0.43***	0.16	0.02
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.42***	**0.41***	**0.42***	**0.46***
Pre-sidedress Soil NO_3-N at the 0N and 0-30 cm depth ($PSNT_0$0-30)	**0.50***	0.10	0.30	**0.81***
Pre-sidedress Soil NO_3-N at the 45N and 0-30 cm depth ($PSNT_{45}$0-30)	**0.58***	-0.12	**0.54***	**0.82***

† $NDRE_0$225 and $NDRE_0$270 = [NDRE at 0N (red edge at 0N/near infrared at 0N)/NDRE at 225 or 270N (red edge at 225 or 270N/near infrared at 225 or 270N)] and $NDRE_{45}$225 and $NDRE_{45}$270 = [NDRE at 45N (red edge at 45N/near infrared at 45N)/NDRE at 225 or 270N (red edge at 225 or 270N/near infrared at 225 or 270N)].
‡ SI_{RE0} = (red edge at 0N/near infrared at 0N) and SI_{RE45} = red edge at 45N/near infrared at 45N).

Table 32. Correlation (r) between plant variables at the 0 (0N), 45 kg N ha^{-1} (45N), and economic optimum N rate (EONR) and internal N efficiency at the economic optimum N rate for eight states in and across three years (2014, 2015, and 2016), two productivity sites (high and low based on historical yield data), and N application timings (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage). Significant correlations ($p \leq 0.10$) with * and bolded.

Plant Variables	All	2014	2015	2016
	r			
Economic Optimum N Rate (EONR)	-0.04	0.06	0.18	-0.20
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	-0.07	-0.15	-0.19	0.00
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**-0.68***	**-0.69***	**-0.61***	**-0.71***
R6 Total Plant N Content at the Economic Optimum N Rate (PMN_E)	**-0.65***	**-0.57***	**-0.67***	**-0.74***
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**-0.61***	**-0.64***	**-0.33***	**-0.70***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**-0.59***	**-0.56***	**-0.85***	**-0.58***
Tasseling Plant N Content at 0N (VTN_0)	**-0.42***	**-0.72***	**-0.53***	**-0.32***
Tasseling Plant N Content at 45N (VTN_{45})	**-0.50***	**-0.74***	**-0.52***	**-0.56***
R6 Plant N Content at 0N (PMN_0)	**-0.28***	**-0.38***	**-0.41***	-0.23
R6 Plant N Content at 45N (PMN_{45})	**-0.35***	**-0.44***	**-0.36***	**-0.44***
Harvest Index at 0N (HI_0)	**0.39***	**0.48***	-0.09	**0.61***
Harvest Index at 45N (HI_{45})	**0.44***	**0.56***	-0.14	**0.65***
Nitrogen Harvest Index at 0N (NHI_0)	**0.36***	**0.56***	0.17	**0.42***
Nitrogen Harvest Index at 45N (NHI_{45})	**0.47***	**0.67***	0.12	**0.58***
Net Change in Stover N at 0N (ΔNCS_0)	**0.23***	**0.58***	**0.38***	0.06
Net Change in Stover N at 45N (ΔNCS_{45})	**0.23***	**0.57***	**0.36***	0.06

Table 33. Correlation (r) between plant variables (plant N content at tasseling (VTN), physiological maturity total plant N content (PMN), harvest index (HI), nitrogen harvest index (NHI), and net change in stover N between tasseling and maturity (ΔNCS) at two N treatments (non-fertilized (0N) and 45 kg N ha^{-1} (45N)) and internal N efficiency components at the economic optimum N rate, soil, and crop reflectance variables at eight states in and across three years (2014, 2015, and 2016) and two productivity sites (high and low based on historical yield data). Significant correlations ($p \leq 0.10$) with * and bolded.

Plant N Content at Tasseling at 0N (VTN_0)	All	2014	2015	2016
	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	**0.27***	**0.48***	**0.43***	-0.25
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.38***	**0.34***	**0.58***	**0.42***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.42***	**0.71***	**0.57***	0.05
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**0.21***	**0.79***	0.05	-0.16
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**0.45***	**0.59***	**0.55***	0.28
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	**0.33***	**0.53***	0.15	**0.35***
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**0.59***	**0.51***	**0.48***	**0.79***
Normalized Difference Vegetative Index Target (0N) / NDVI at the 225 kg N ha^{-1} ($NDVI_0225$)	**0.46***	**0.50***	**0.56***	**0.31***
Normalized Difference Vegetative Index Target (0N) / NDVI at the 270 kg N ha^{-1} ($NDVI_0270$)	**0.44***	**0.52***	**0.47***	**0.40***
Normalized Difference Vegetative Index Target (45N) / NDVI at the 225 kg N ha^{-1} ($NDVI_{45}225$)	**0.52***	**0.44***	**0.58***	**0.53***
Normalized Difference Vegetative Index Target (45N) / NDVI at the 270 kg N ha^{-1} ($NDVI_{45}270$)	**0.45***	**0.44***	**0.41***	**0.56***
Simple Ratio Sufficiency Index of Red Reflectance at the 0N (SI_{R0})	**0.51***	**0.42***	**0.57***	**0.54***
Simple Ratio Sufficiency Index of Red Reflectance at the 45N (SI_{R45})	**0.54***	**0.38***	**0.55***	**0.75***
Normalized Difference Red Edge Index Target (0N) / NDRE at the 225 kg N ha^{-1} ($NDRE_0225$)	**0.53***	**0.49***	**0.53***	**0.64***
Normalized Difference Red Edge Index Target (0N) / NDRE at the 270 kg N ha^{-1} ($NDRE_0270$)	**0.52***	**0.52***	**0.47***	**0.66***
Normalized Difference Red Edge Index Target (45N) / NDRE at the 225 kg N ha^{-1} ($NDRE_{45}225$)	**0.53***	**0.49***	**0.52***	**0.66***
Normalized Difference Red Edge Index Target (45N) / NDRE at the 270 kg N ha^{-1} ($NDRE_{45}270$)	**0.51***	**0.53***	**0.44***	**0.72***
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 0N (SI_{RE0})	**0.49***	**0.40***	**0.43***	**0.68***
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 45N (SI_{RE45})	**0.42***	0.16	**0.46***	**0.73***

Table 33. Continued.

Plant N Content at Tasseling at 45N (VTN_{45})	All	2014	2015	2016
	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	**0.36***	**0.40***	**0.42***	0.08
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.34***	0.29	**0.60***	0.28
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.54***	**0.66***	**0.55***	**0.43***
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**0.40***	**0.57***	**0.53***	**0.51***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**0.51***	**0.78***	0.07	**0.34***
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	**0.36***	**0.62***	0.16	**0.35***
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**0.49***	**0.36***	**0.50***	**0.57***
Normalized Difference Vegetative Index Target (0N) / NDVI at the 225 kg N ha^{-1} ($NDVI_0225$)	**0.55***	**0.56***	**0.65***	**0.45***
Normalized Difference Vegetative Index Target (0N) / NDVI at the 270 kg N ha^{-1} ($NDVI_0270$)	**0.51***	**0.60***	**0.56***	**0.45***
Normalized Difference Vegetative Index Target (45N) / NDVI at the 225 kg N ha^{-1} ($NDVI_{45}225$)	**0.59***	**0.53***	**0.67***	**0.58***
Normalized Difference Vegetative Index Target (45N) / NDVI at the 270 kg N ha^{-1} ($NDVI_{45}270$)	**0.48***	**0.55***	**0.50***	**0.49***
Simple Ratio Sufficiency Index of Red Reflectance at the 0N (SI_{R0})	**0.53***	**0.45***	**0.68***	**0.45***
Simple Ratio Sufficiency Index of Red Reflectance at the 45N (SI_{R45})	**0.57***	**0.43***	**0.66***	**0.65***
Normalized Difference Red Edge Index Target (0N) / NDRE at the 225 kg N ha^{-1} ($NDRE_0225$)	**0.51***	**0.50***	**0.61***	**0.43***
Normalized Difference Red Edge Index Target (0N) / NDRE at the 270 kg N ha^{-1} ($NDRE_0270$)	**0.48***	**0.51***	**0.54***	**0.42***
Normalized Difference Red Edge Index Target (45N) / NDRE at the 225 kg N ha^{-1} ($NDRE_{45}225$)	**0.54***	**0.57***	**0.59***	**0.49***
Normalized Difference Red Edge Index Target (45N) / NDRE at the 270 kg N ha^{-1} ($NDRE_{45}270$)	**0.50***	**0.61***	**0.50***	**0.49***
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 0N (SI_{RE0})	**0.41***	**0.39***	**0.52***	**0.36***
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 45N (SI_{RE45})	**0.35***	0.10	**0.53***	**0.44***

Table 33. Continued.

R6 Total Plant N Content at 0N (PMN_0)	All	2014	2015	2016
	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	**0.40***	**0.68***	**0.46***	-0.03
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.27***	0.13	**0.51***	0.23
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.43***	**0.69***	**0.53***	0.12
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.14	**0.46***	-0.01	-0.01
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**0.43***	**0.67***	**0.51***	0.23
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	**0.22***	0.09	0.26	**0.32***
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**0.55***	0.05	**0.72***	**0.67***
Normalized Difference Vegetative Index Target (0N) / NDVI at the 225 kg N ha^{-1} ($NDVI_0225$)	**0.40***	**0.40***	**0.43***	**0.37***
Normalized Difference Vegetative Index Target (0N) / NDVI at the 270 kg N ha^{-1} ($NDVI_0270$)	**0.42***	**0.41***	**0.43***	**0.44***
Normalized Difference Vegetative Index Target (45N) / NDVI at the 225 kg N ha^{-1} ($NDVI_{45}225$)	**0.39***	**0.34***	**0.35***	**0.49***
Normalized Difference Vegetative Index Target (45N) / NDVI at the 270 kg N ha^{-1} ($NDVI_{45}270$)	**0.37***	**0.32***	0.29	**0.50***
Simple Ratio Sufficiency Index of Red Reflectance at the 0N (SI_{R0})	**0.49***	**0.49***	**0.48***	**0.53***
Simple Ratio Sufficiency Index of Red Reflectance at the 45N (SI_{R45})	**0.47***	**0.61***	**0.33***	**0.63***
Normalized Difference Red Edge Index Target (0N) / NDRE at the 225 kg N ha^{-1} ($NDRE_0225$)	**0.57***	**0.58***	**0.60***	**0.57***
Normalized Difference Red Edge Index Target (0N) / NDRE at the 270 kg N ha^{-1} ($NDRE_0270$)	**0.56***	**0.60***	**0.56***	**0.59***
Normalized Difference Red Edge Index Target (45N) / NDRE at the 225 kg N ha^{-1} ($NDRE_{45}225$)	**0.43***	**0.37***	**0.39***	**0.54***
Normalized Difference Red Edge Index Target (45N) / NDRE at the 270 kg N ha^{-1} ($NDRE_{45}270$)	**0.42***	**0.36***	**0.34***	**0.58***
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 0N (SI_{RE0})	**0.53***	**0.58***	**0.58***	**0.52***
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 45N (SI_{RE45})	**0.43***	**0.53***	**0.37***	**0.52***

Table 33. Continued.

R6 Total Plant N Content at 45N (PMN_{45})	All	2014	2015	2016
	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	**0.52***	**0.68***	**0.57***	0.19
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.25***	0.06	**0.55***	0.20
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**0.57***	**0.71***	**0.57***	**0.45***
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**0.30***	**0.55***	0.11	0.27
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**0.51***	**0.72***	**0.38***	**0.54***
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	**0.28***	0.28	0.26	**0.31***
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**0.46***	0.10	**0.65***	**0.47***
Normalized Difference Vegetative Index Target (0N) / NDVI at the 225 kg N ha^{-1} ($NDVI_0225$)	**0.40***	**0.56***	**0.40***	0.24
Normalized Difference Vegetative Index Target (0N) / NDVI at the 270 kg N ha^{-1} ($NDVI_0270$)	**0.40***	**0.59***	**0.42***	0.26
Normalized Difference Vegetative Index Target (45N) / NDVI at the 225 kg N ha^{-1} ($NDVI_{45}225$)	**0.49***	**0.48***	**0.50***	**0.45***
Normalized Difference Vegetative Index Target (45N) / NDVI at the 270 kg N ha^{-1} ($NDVI_{45}270$)	**0.44***	**0.47***	**0.47***	**0.39***
Simple Ratio Sufficiency Index of Red Reflectance at the 0N (SI_{R0})	**0.41***	**0.61***	**0.42***	0.25
Simple Ratio Sufficiency Index of Red Reflectance at the 45N (SI_{R45})	**0.52***	**0.66***	**0.47***	**0.49***
Normalized Difference Red Edge Index Target (0N) / NDRE at the 225 kg N ha^{-1} ($NDRE_0225$)	**0.52***	**0.68***	**0.57***	**0.34***
Normalized Difference Red Edge Index Target (0N) / NDRE at the 270 kg N ha^{-1} ($NDRE_0270$)	**0.51***	**0.71***	**0.56***	**0.32***
Normalized Difference Red Edge Index Target (45N) / NDRE at the 225 kg N ha^{-1} ($NDRE_{45}225$)	**0.50***	**0.54***	**0.54***	**0.39***
Normalized Difference Red Edge Index Target (45N) / NDRE at the 270 kg N ha^{-1} ($NDRE_{45}270$)	**0.49***	**0.56***	**0.51***	**0.38***
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 0N (SI_{RE0})	**0.44***	**0.65***	**0.51***	0.26
Simple Ratio Sufficiency Index of Red Edge Reflectance at the 45N (SI_{RE45})	**0.43***	**0.48***	**0.51***	**0.33***

Table 33. Continued.

Harvest Index at 0N (HI_0)	All	2014	2015	2016
	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.15	-0.10	**0.49***	0.06
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	-0.10	**-0.36***	**0.33***	-0.24
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	-0.17	**-0.30***	**0.38***	**-0.46***
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**-0.62***	**-0.68***	**-0.33***	**-0.76***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.08	0.13	**0.40***	-0.14
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	**-0.24***	**-0.46***	-0.26	-0.09
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.26***	0.07	**0.48***	0.23
Pre-Sidedress Soil NO_3-N 0-30 cm at 0N ($PSNT_0$0-30)	**0.40***	0.24	**0.45***	**0.41***
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	**0.33***	**0.43***	**0.60***	**0.30***
Harvest Index at 45N (HI_{45})				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	**0.26***	0.14	**0.55***	0.08
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	-0.13	**-0.53***	**0.43***	-0.25
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	-0.12	-0.15	**0.45***	**-0.51***
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**-0.59***	**-0.51***	-0.30	**-0.80***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	0.06	0.14	**0.41***	-0.20
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	**-0.24***	**-0.35***	**-0.33***	-0.16
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.27***	-0.01	**0.56***	0.24
Pre-Sidedress Soil NO_3-N 0-30 cm at 0N ($PSNT_0$0-30)	**0.38***	0.24	**0.43***	**0.36***
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	**0.36***	**0.37***	**0.61***	0.28

Table 33. Continued.

Nitrogen Harvest Index at 0N (NHI_0)	All	2014	2015	2016
	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	-0.07	**-0.34***	**0.64***	**-0.44***
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**0.22***	-0.13	**0.41***	0.23
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**-0.32***	**-0.52***	**0.35***	**-0.66***
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**-0.63***	**-0.80***	-0.28	**-0.76***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**-0.35***	**-0.31***	0.04	**-0.59***
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	**-0.39***	**-0.50***	**-0.33***	**-0.40***
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.25***	-0.12	**0.39***	**0.40***
Pre-Sidedress Soil NO_3-N 0-30 cm at 0N ($PSNT_0$0-30)	**0.35***	0.01	**0.46***	**0.46***
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	**0.48***	**0.47***	**0.55***	**0.58***
Nitrogen Harvest Index at 45N (NHI_{45})				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.00	-0.20	**0.63***	**-0.36***
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	0.15	-0.21	**0.46***	0.10
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	**-0.34***	**-0.47***	**0.36***	**-0.74***
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	**-0.62***	**-0.66***	-0.25	**-0.82***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**-0.45***	**-0.52***	0.02	**-0.70***
SSURGO Plant Available Water Content at the 0-30 cm depth (PAWC0-30)	**-0.37***	**-0.30***	**-0.38***	**0.46***
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**0.25***	-0.25	**0.44***	**0.37***
Pre-Sidedress Soil NO_3-N 0-30 cm at 0N ($PSNT_0$0-30)	**0.33***	-0.01	**0.39***	**0.42***
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	**0.48***	0.24	**0.54***	**0.57***

Table 33. Continued.

Net Change in Stover N Content between Tasseling and Physiological Maturity at 0N (ΔNCS_0)	All	2014	2015	2016
	r			
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.03	-0.22	0.19	**0.37***
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**-0.28***	**-0.39***	-0.26	**-0.39***
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	-0.12	**-0.49***	-0.02	0.23
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.03	**-0.65***	0.32	**0.46***
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**-0.26***	**-0.33***	**-0.45***	-0.01
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**-0.39***	0.00	**-0.34***	**-0.69***
Pre-Sidedress Soil NO_3-N 0-30 cm at 0N ($PSNT_0$0-30)	**-0.28***	0.24	0.06	**-0.76***
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	**-0.35***	0.25	-0.20	**-0.60***
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**-0.58***	**-0.59***	**-0.42***	**-0.68***
Net Change in Stover N Content between Tasseling and Physiological Maturity at 45N (ΔNCS_{45})				
Grain Dry Matter at the Economic Optimum N Rate (GDM_E)	0.07	0.07	0.25	0.14
Grain N Concentration at the Economic Optimum N Rate (GNC_E)	**-0.27***	**-0.52***	-0.26	-0.24
R6 Plant N Content at the Economic Optimum N Rate (PMN_E)	-0.08	-0.27	0.01	0.15
R6 Stover Dry Matter at the Economic Optimum N Rate (SDM_E)	0.01	**-0.40***	**0.32***	0.23
R6 Stover N Concentration at the Economic Optimum N Rate (SNC_E)	**-0.20***	-0.15	**-0.42***	0.06
Pre-plant Soil NO_3-N at the 0-30 cm depth (PPNT0-30)	**-0.19***	0.17	-0.26	**-0.37***
Pre-Sidedress Soil NO_3-N 0-30 cm at 0N ($PSNT_0$0-30)	**-0.14***	**0.44***	0.07	**-0.62***
Tasseling Soil NO_3-N 0-30 cm at 0N ($VTNT_0$0-30)	-0.12	**0.38***	-0.12	-0.18
PPNT0-60*Silt Content*$HT_{2wkBAVT}$	**-0.43***	-0.10	**-0.43***	**-0.54***

Table 34. Predictive equations for internal N efficiency at the economic optimal N rate at different times of the growing season. Variables used in one or more models were clay content, pH salt (pH_s), pH water (pH_w), weighted mean for organic matter in the Ap horizon determine by total organic carbon (OM_2) or thermo gravimetric analyzer (OM_3), cation exchange capacity (CEC), plant available water content at the 0-30 (PAWC0-30) and 60-90 cm depths (PAWC60-90), pre-plant NO_3-N averaged over the 0-30 and 30-60 cm depth (PPNT0-60) and pre-sidedress soil NO_3-N (V5±1 V-stage) 0-30 cm depth from the 45 kg N ha^{-1} treatment ($PSNT_{45}$0-30), sufficiency indices for normalized difference vegetative index ($NDVI_{45}$/$NDVI_{225}$) ($NDVI_{45}$225) and normalized difference red edge at the 45 kg ha^{-1} ($NDRE_{45}$), plant N content at tasseling from the 45 kg N ha^{-1} treatment (VTN_{45}), adequate and well-distributed rainfall ten days before or after split-applied N ($AWDR_{10dBSN}$ and $AWDR_{10dASN}$). Equations were determined from N rate experiments conducted in eight states over a three year period (2014, 2015, and 2016) across two productivity sites (low and high based on historical yield data), N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage), and N rates ranging from 0 to 315 kg N ha^{-1} in increments of 45 kg N ha^{-1}.

Prediction timing	Variables	Estimates	Significance†	C(p)	Partial R²	Model Adj. R²
At-planting (n = 88)	Intercept	72.7 ± 4.2				0.19
	PAWC0-30 (cm cm^{-1})	-82.5 ± 19.6	**	5	0.16	
	PPNT0-60 (mg kg^{-1})	-0.2958 ± 0.1302	**	2	0.21	
Sidedress (V9±1 V-stage) (n = 84)	Intercept	136.6 ± 16.6				0.47
	PAWC0-30 (cm cm^{-1})	-70.6 ± 18.7	**	227	0.18	
	$NDVI_{45}$225	-50.3 ± 18.9	**	203	0.25	
	OM_3 (g kg^{-1})	0.3276 ± 0.0775	**	183	0.31	
	CEC (meq 100 g^{-1})	-0.3099 ± 0.1037	**	164	0.37	
	$PSNT_{45}$0-30 (mg kg^{-1})	0.3666 ± 0.1189	**	152	0.40	
	PPNT0-60 (mg kg^{-1})	-0.3091 ± 0.1635	**	136	0.45	
	$NDRE_0$	-42.9 ± 14.0	**	123	0.49	
	pH_s	-2.0 ± 1.0	**	115	0.52	
Post-Sidedress (V11 to prior to VT) (n = 84)	Intercept	135.9 ± 14.5				0.62
	PAWC0-30 (cm cm^{-1})	-69.9 ± 15.9	**	234	0.18	
	$NDVI_{45}$225	-43.5 ± 16.9	**	210	0.25	
	$AWDR_{10dASN}$	0.1431 ± 0.0241	**	185	0.32	
	OM_3 (g kg^{-1})	0.3294 ± 0.0643	**	164	0.38	
	CEC (meq 100 g^{-1})	-0.3556 ± 0.0876	**	141	0.45	
	$PSNT_{45}$0-30 (mg kg^{-1})	0.4034 ± 0.1023	**	119	0.51	
	PPNT0-60 (mg kg^{-1})	-0.4565 ± 0.1379	**	101	0.56	
	$NDRE_{45}$	-50.4 ± 11.6	**	78	0.63	
	pH_w	-2.1 ± 0.8627	**	70	0.65	
	$AWDR_{10dBSN}$	-0.0323 ± 0.0180	**	67	0.67	

Table 34. Continued.

Prediction timing	Variables	Estimates	Significance†	C(p)	Partial R^2	Model Adj. R^2
VT or Later (n = 70)	Intercept	72.5 ± 3.9				0.54
	VTN_{45} (kg ha^{-1})	-0.0749 ± 0.0130	**	138	0.34	
	PAWC60-90 (cm cm^{-1})	-67.6 ± 17.4	**	108	0.45	
	OM_2 (g kg^{-1})	0.1535 ± 0.0498	**	97	0.49	
	Clay (g kg^{-1})	-0.0159 ± 0.0054	**	85	0.53	
	$AWDR_{10dASN}$	0.0782 ± 0.0298	**	73	0.58	

† Estimate of the variable significant at $p \leq 0.10$.

Table 35. Average (± standard deviation) physiological maturity total plant N content (PMN) and net change in stover N content between tasseling and maturity (ΔNCS) at the non-fertilizer and 45 kg N ha^{-1} treatments for eight state over a three year period (2014, 2015, and 2016) and two productivity sites (Prod. – high (H) and low (L) based on historical yield data).

Year	State	Prod.	PMN_0	PMN_{45}	ΔNCS_0	ΔNSC_{45}
			---------------------------- kg N ha^{-1}			---------------------------------
2014	IA	H	73 ± 7	118 ± 13	-19 ± 9	-33 ± 13
2014	IA	L	116 ± 20	157 ± 9	-31 ± 23	-68 ± 18
2014	IL	H	62 ± 10	97 ± 17	-36 ± 6	-41 ± 18
2014	IL	L	59 ± 8	82 ± 24	-29 ± 9	-31 ± 23
2014	IN	H	97 ± 9	128 ± 11	-30 ± 18	-51 ± 22
2014	IN	L	122 ± 9	141 ± 18	-26 ± 25	-41 ± 14
2014	MN	H	82 ± 18	95 ± 17	-23 ± 3	-40 ± 11
2014	MN	L	73 ± 8	124 ± 13	-40 ± 3	-53 ± 11
2014	MO	H	115 ± 15	172 ± 34	-96 ± 30	-126 ± 29
2014	MO	L	101 ± 29	138 ± 27	-106 ± 36	-107 ± 22
2014	ND	H	100 ± 41	118 ± 17	-24 ± 49	-86 ± 13
2014	ND	L	36 ± 15	57 ± 17	-22 ± 17	-77 ± 14
2014	NE	H	214 ± 33	265 ± 28	-22 ± 33	-34 ± 17
2014	NE	L	117 ± 32	124 ± 36	-20 ± 14	-30 ± 4
2014	WI	H	133 ± 12	185 ± 15	-35 ± 30	-29 ± 25
2014	WI	L	128 ± 3	158 ± 15	-15 ± 19	-8 ± 26

Table 35. Continued.

Year	State	Prod.	PMN_0	PMN_{45}	ΔNCS_0	ΔNSC_{45}
			---------------------------- kg N ha^{-1}	---------------------------------		
2015	IA	H	92 ± 21	129 ± 19	-54 ± 27	-70 ± 26
2015	IA	L	70 ± 6	121 ± 16	-60 ± 13	-58 ± 12
2015	IL	H	91 ± 14	111 ± 16	-37 ± 23	-48 ± 14
2015	IL	L	86 ± 23	133 ± 47	-30 ± 14	-57 ± 19
2015	IN	H	75 ± 13	96 ± 14	-51 ± 8	-58 ± 14
2015	IN	L	77 ± 14	108 ± 16	-1 ± 12	1 ± 22
2015	MN	H	111 ± 17	178 ± 16	-30 ± 8	-42 ± 11
2015	MN	L	155 ± 19	172 ± 20	-40 ± 14	-71 ± 19
2015	MO	H	58 ± 16	83 ± 6	-38 ± 23	-65 ± 31
2015	MO	L	56 ± 11	44 ± 16	-34 ± 5	-59 ± 8
2015	ND	H	-†	-	-	-
2015	ND	L	-	-	-	-
2015	NE	H	243 ± 20	263 ± 22	-58 ± 25	-73 ± 17
2015	NE	L	81 ± 7	83 ± 6	-50 ± 10	-61 ± 32
2015	WI	H	188 ± 16	201 ± 29	-89 ± 40	-126 ± 34
2015	WI	L	124 ± 23	154 ± 18	-113 ± 20	-143 ± 26

Table 35. Continued.

Year	State	Prod.	PMN_0	PMN_{45}	ΔNCS_0	ΔNSC_{45}
			----------------------------	kg N ha^{-1}	---------------------------------	
2016	IA	H	126 ± 16	179 ± 38	-19 ± 15	-94 ± 32
2016	IA	L	113 ± 13	135 ± 14	-28 ± 20	-66 ± 34
2016	IL	H	88 ± 17	132 ± 15	-83 ± 11	-110 ± 21
2016	IL	L	88 ± 13	117 ± 24	-52 ± 14	-62 ± 29
2016	IN	H	83 ± 10	124 ± 6	-41 ± 11	-72 ± 12
2016	IN	L	127 ± 9	176 ± 15	-55 ± 13	-82 ± 3
2016	MN	H	39 ± 11	76 ± 36	-26 ± 9	-42 ± 26
2016	MN	L	82 ± 16	129 ± 35	-39 ± 11	-77 ± 9
2016	MO	HA	134 ± 17	221 ± 47	-43 ± 26	-35 ± 59
2016	MO	HB	106 ± 13	152 ± 2	-53 ± 23	-68 ± 34
2016	MO	L	94 ± 5	135 ± 35	-107 ± 14	-125 ± 76
2016	ND	H	166 ± 31	173 ± 34	-85 ± 25	-88 ± 30
2016	ND	L	151 ± 47	165 ± 49	-94 ± 23	-81 ± 35
2016	NE	H	158 ± 22	192 ± 13	-62 ± 25	-64 ± 16
2016	NE	L	131 ± 35	156 ± 40	0 ± 0	0 ± 0
2016	WI	H	174 ± 31	189 ± 2	-86 ± 41	-128 ± 20
2016	WI	L	119 ± 17	150 ± 13	0 ± 0	0 ± 0

† Grain N and cob N data missing.

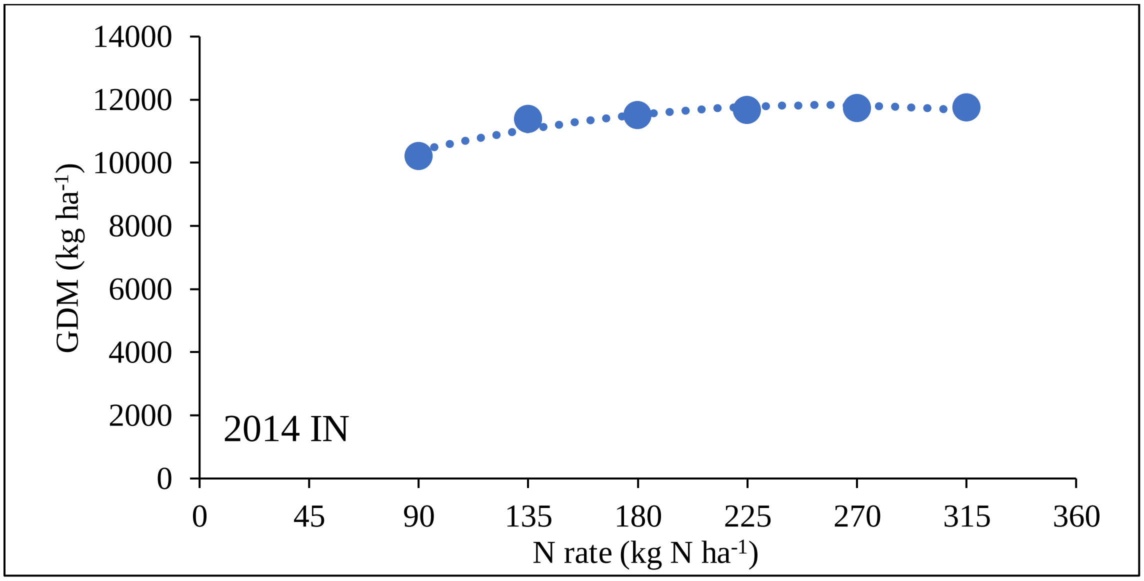

Figure 1. Grain dry matter (GDM) (averaged over N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) and productivity site (low and high based on historical yield data)) quadratic response to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) ($p \leq 0.10$) at 2014 IN state-year. Each data point represents GDM at a specific N rate averaged over four replications.

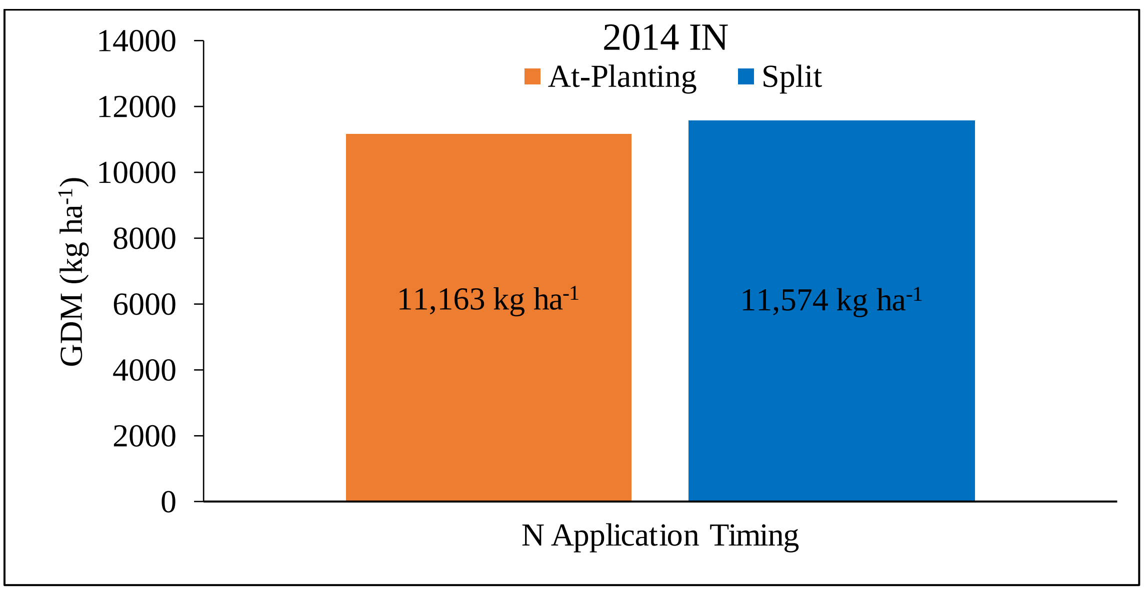

Figure 2. Grain dry matter (GDM) (averaged over N rates (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) and productivity site (low and high based on historical yield data)) response to N application timing ($p \leq 0.10$) at 2014 IN state-year.

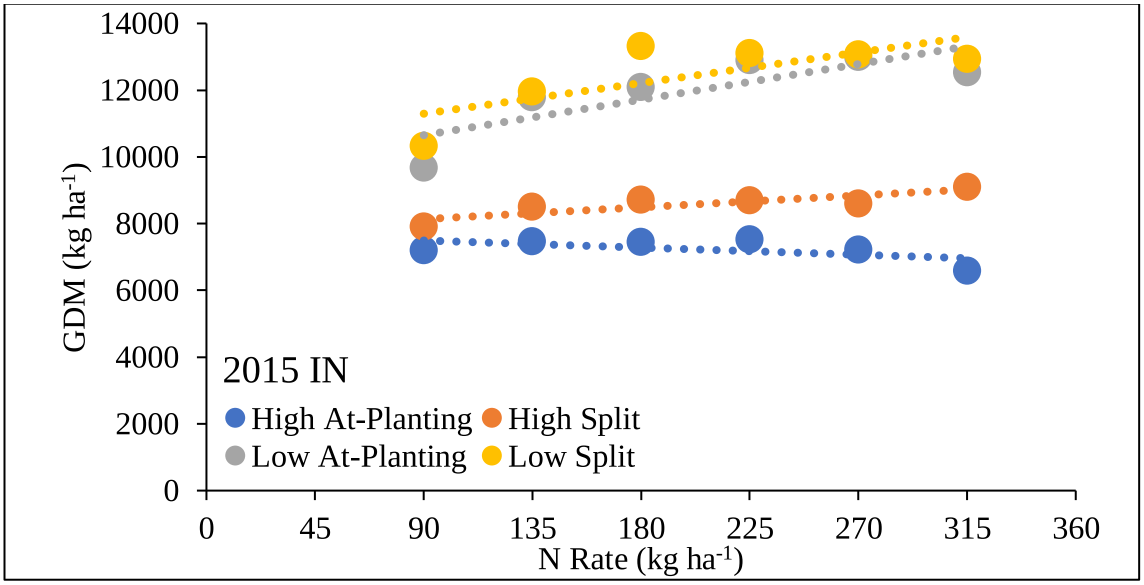

Figure 3. Grain dry matter (GDM) linear response ($p \leq 0.10$) to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments), timing (all ‘at-planting’ or ‘split’ with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) and productivity site (low and high based on historical yield data) in 2015 IN. Each data point represents GDM at a specific N rate, productivity site, and timing.

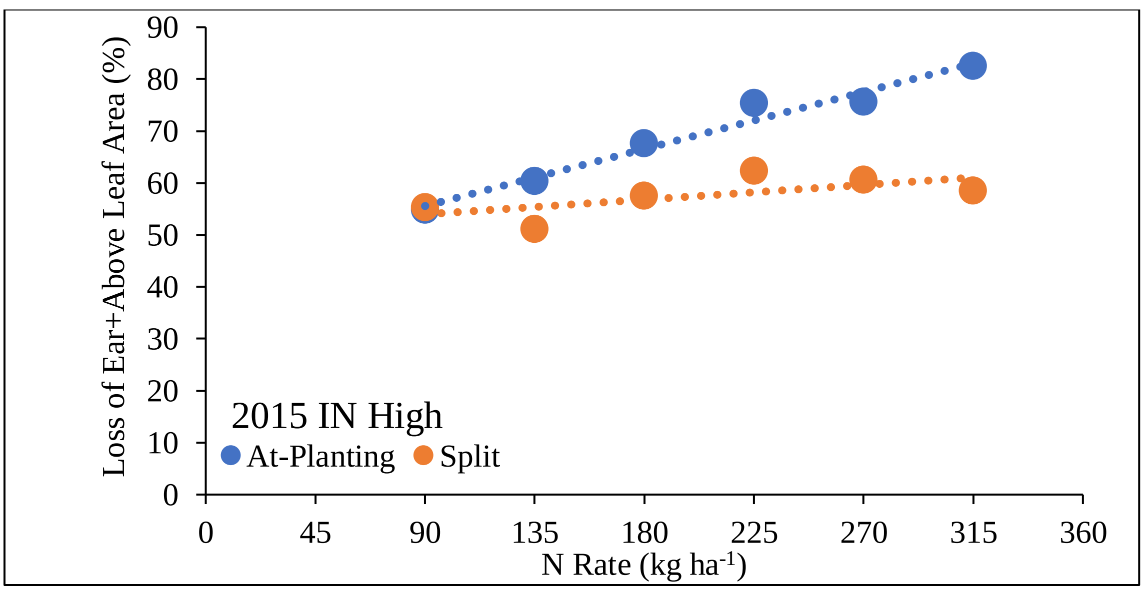

Figure 4. Nitrogen rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) and timing (all ‘at-planting’ or ‘split’ with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) effect on the loss of percent green leaf area of the ear leaf plus the first leaf above the ear leaf to Northern Corn Leaf Blight (caused by *Exserohilum turcicum*) in 2015 IN at the high productivity site. Each data point represents the percent loss of leaf area averaged over four replications at a specific N rate, productivity site, and timing.

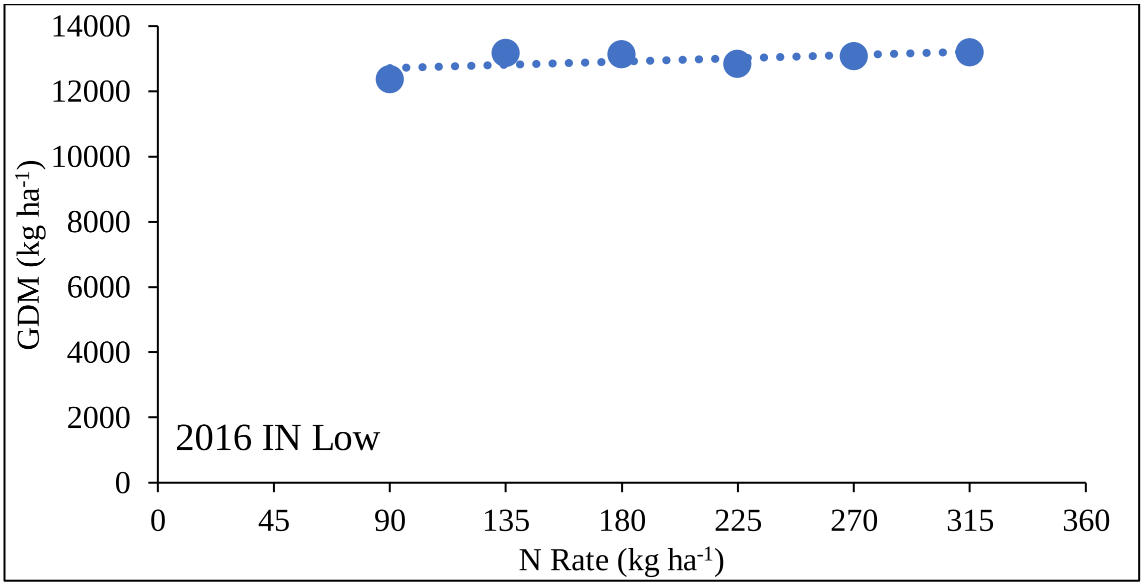

Figure 5. Grain dry matter (GDM) linear response ($p \leq 0.10$) to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) at the low productivity site (based on historical yield data) in 2016 IN. Each data point represents GDM at a specific N rate averaged over four replications.

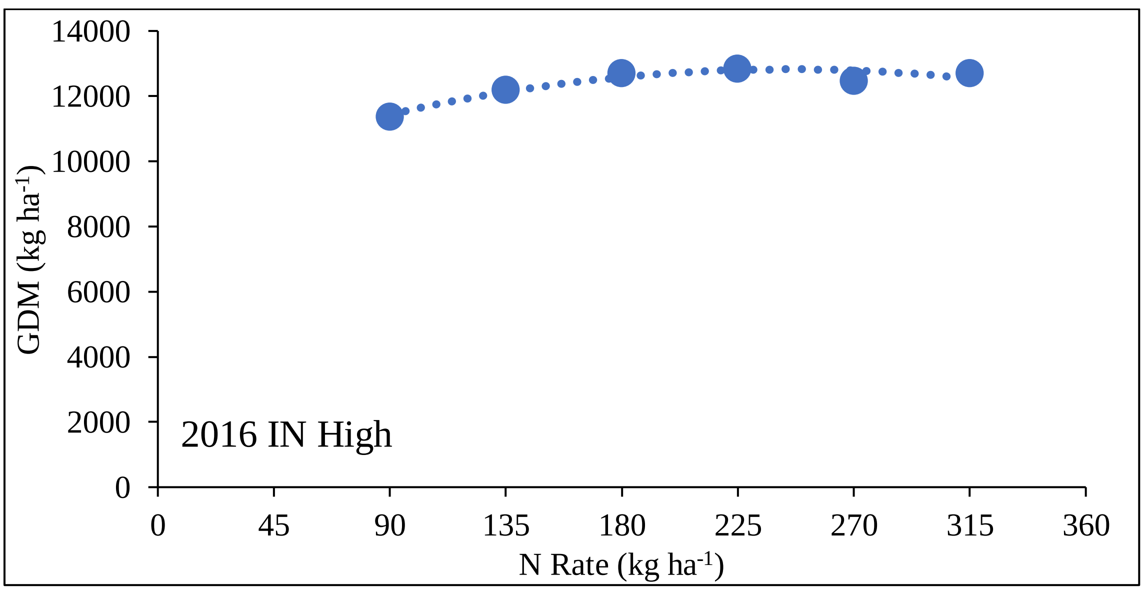

Figure 6. Grain dry matter (GDM) (averaged over N application timing (all ‘at-planting’ or ‘split’ with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) quadratic response ($p \leq 0.10$) to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) at the high productivity site (based on historical yield data) in 2016 IN. Each data point represents GDM at a specific N rate averaged over four replications.

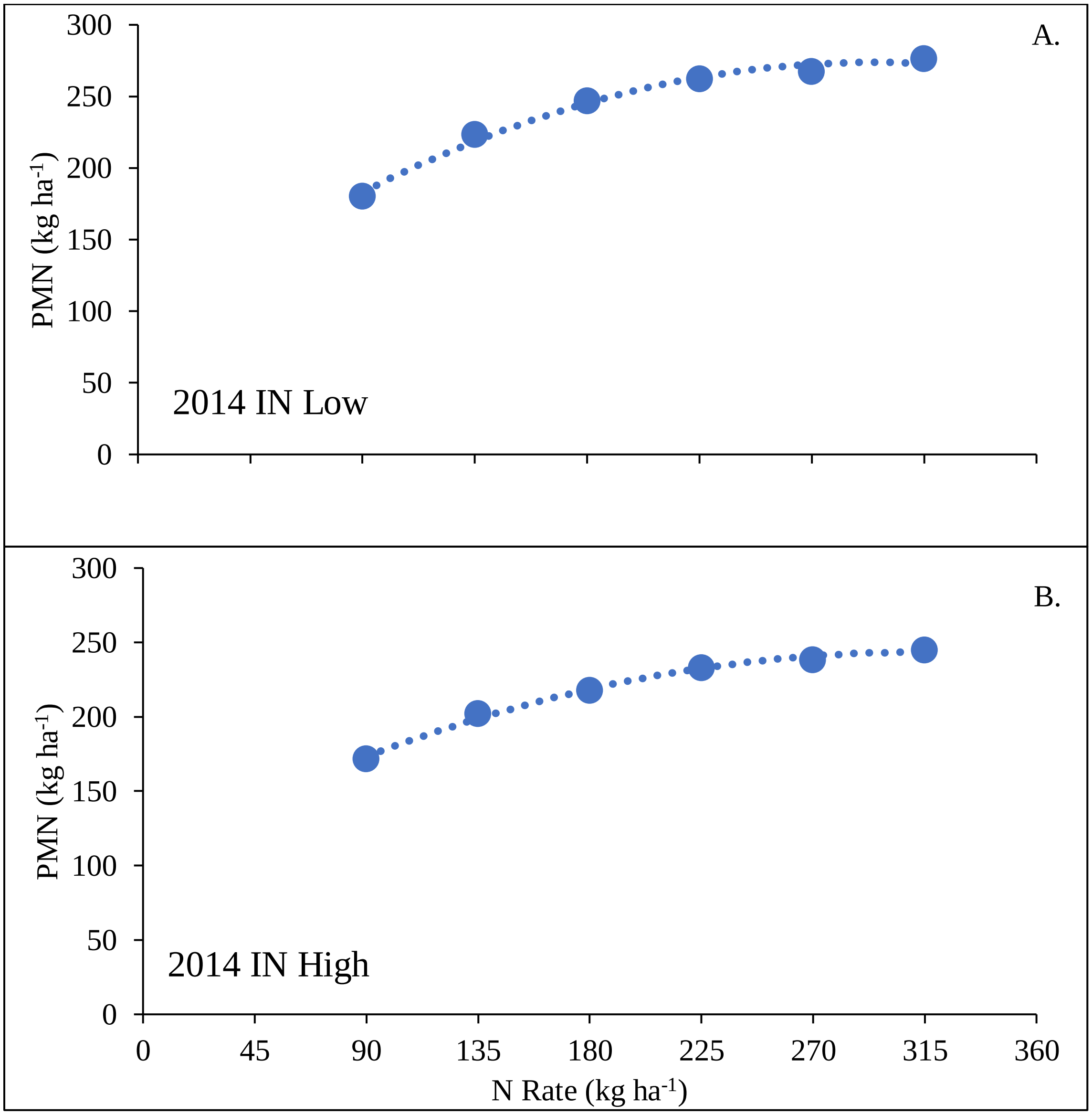

Figure 7A-B. Plant N content at maturity (PMN) (averaged over N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) quadratic response ($p \leq 0.10$) to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) at the low (A) and high (B) productivity sites (based on historical yield data) in 2014 IN. Each data point represents PMN at a specific N rate averaged over four replications.

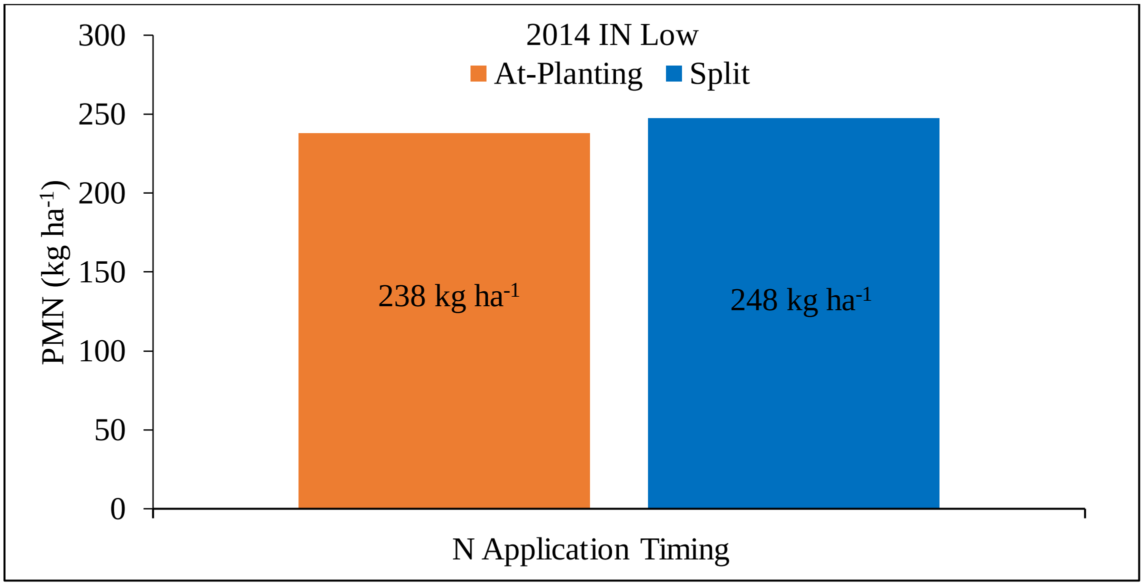

Figure 8. Plant N content at maturity (PMN) response to ($p \leq 0.10$) N application timing (all ‘at-planting’ or ‘split’ with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) at the low productivity site (based on historical yield data) in 2014 IN.

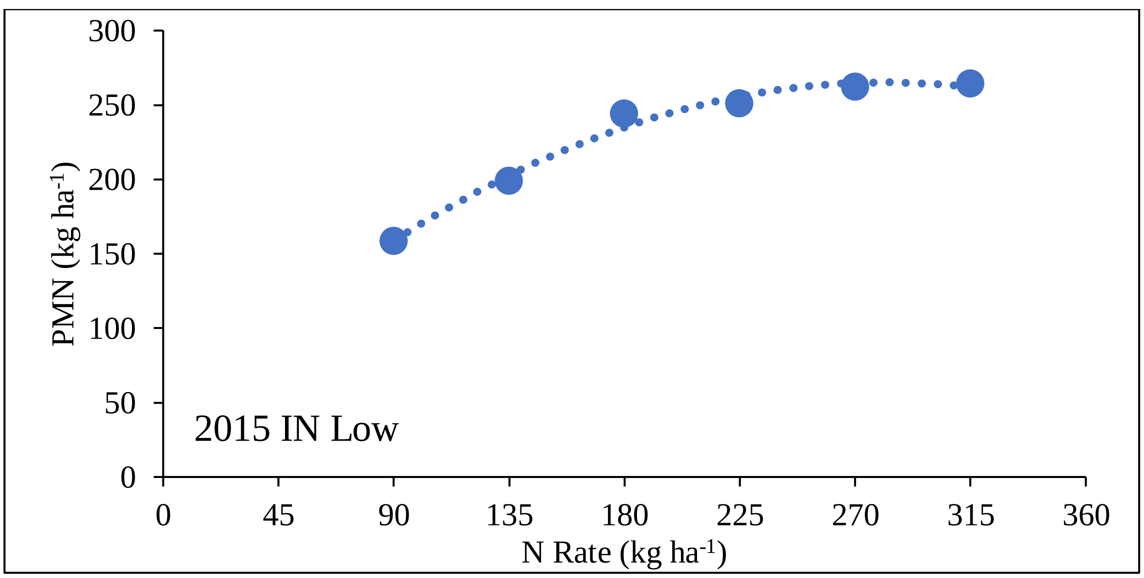

Figure 9. Plant N content at maturity (PMN) (averaged over N application timing (all ‘at-planting’ or ‘split’ with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) quadratic response ($p \leq 0.10$) to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) at the low productivity site (based on historical yield data) in 2015 IN. Each data point represents PMN at a specific N rate averaged over four replications.

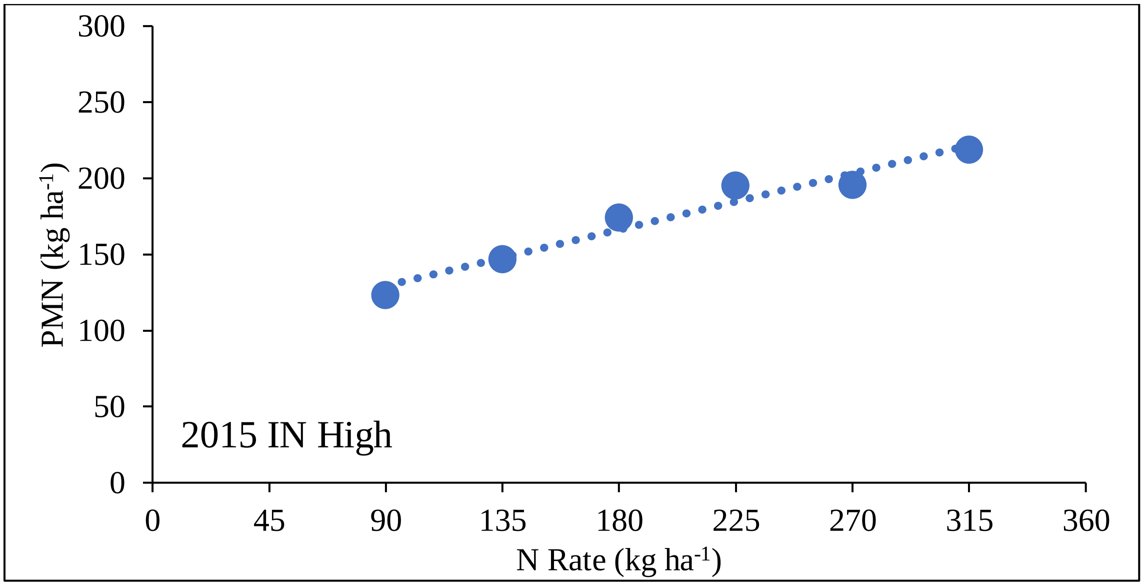

Figure 10. Plant N content at maturity (PMN) (averaged over N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) linear response ($p \leq 0.10$) to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) at the high productivity site (based on historical yield data) in 2015 IN. Each data point represents PMN at a specific N rate averaged over four replications.

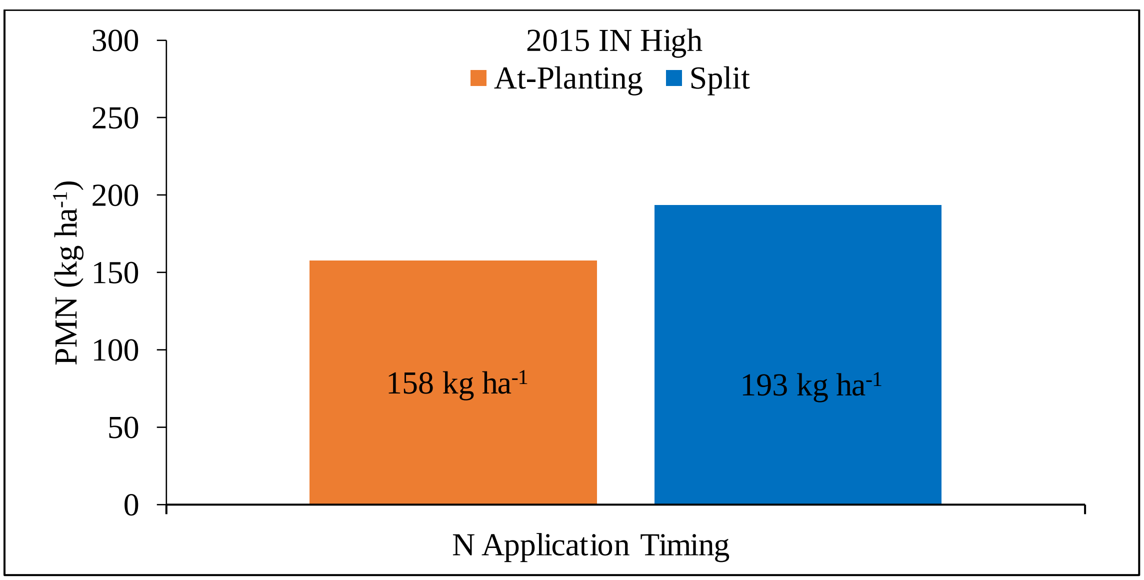

Figure 11. Plant N content at maturity (PMN) response to ($p \leq 0.10$) N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) at the high productivity site (based on historical yield data) in 2015 IN.

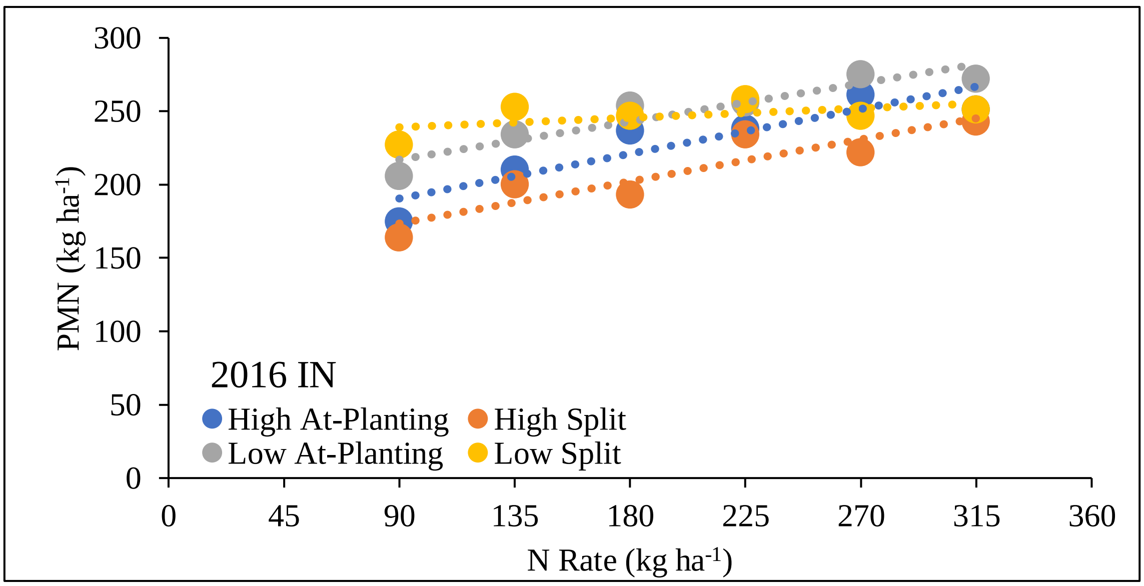

Figure 12. Plant N content at maturity (PMN) linear response ($p \leq 0.10$) to N rate (90 to 315 kg N ha-1 in 45 kg N ha-1), timing (all 'at-planting' or 'split' with 45 kg N ha-1 at planting and the remainder at V9±1 V-stage) and productivity site (low and high based on historical yield data) in 2016 IN. Each data point represents PMN at a specific N rate, productivity site, and timing averaged over four replications.

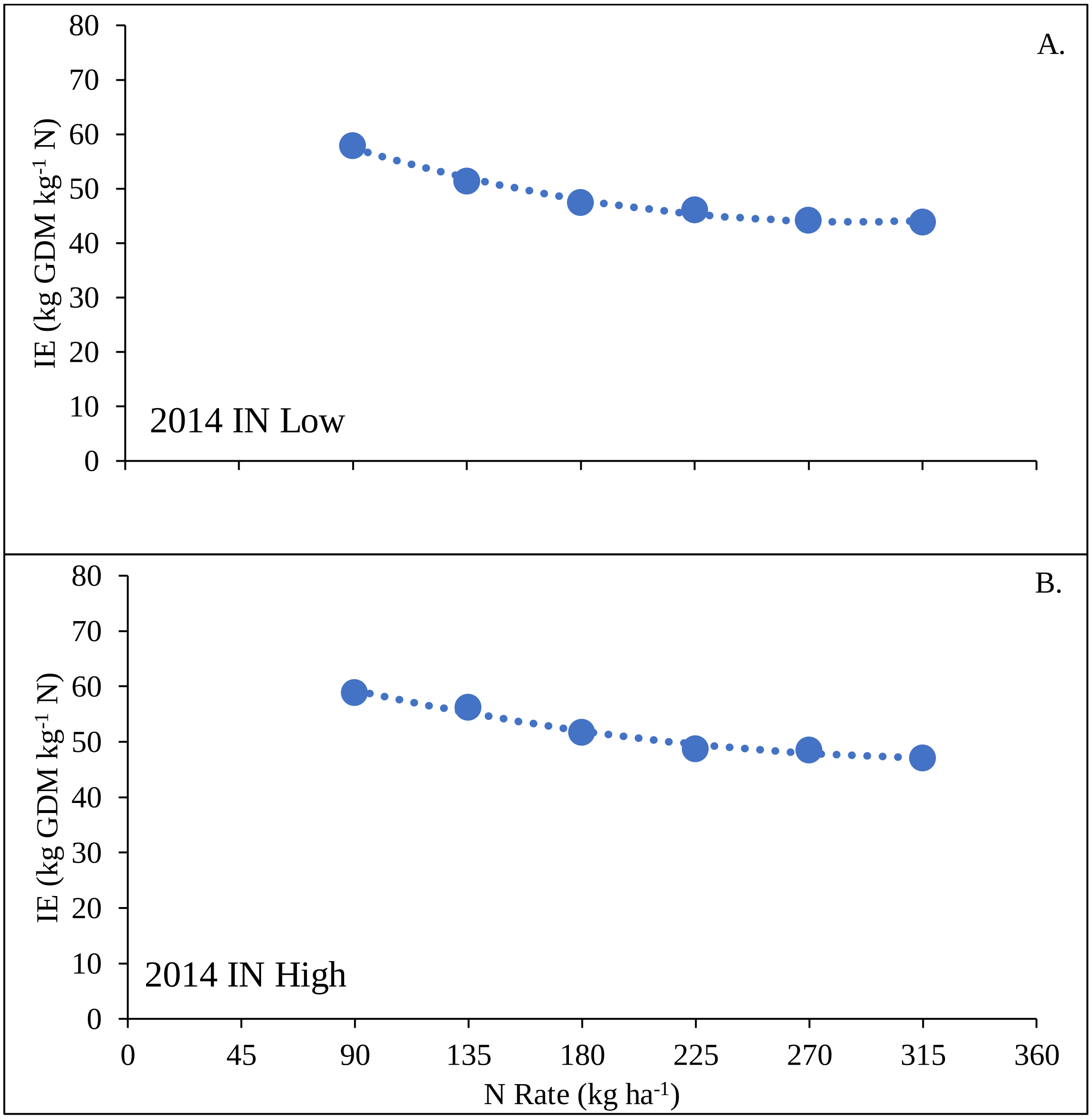

Figure 13A-B. Internal N efficiency (IE = grain dry matter (GDM)/total plant N content at maturity) (averaged over N application timing (all ‘at-planting’ or ‘split’ with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) quadratic response ($p \leq 0.10$) to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) at the low (A) and high (B) productivity site (based on historical yield data) in 2014 IN. Each data point represents IE at a specific N rate averaged over four replications.

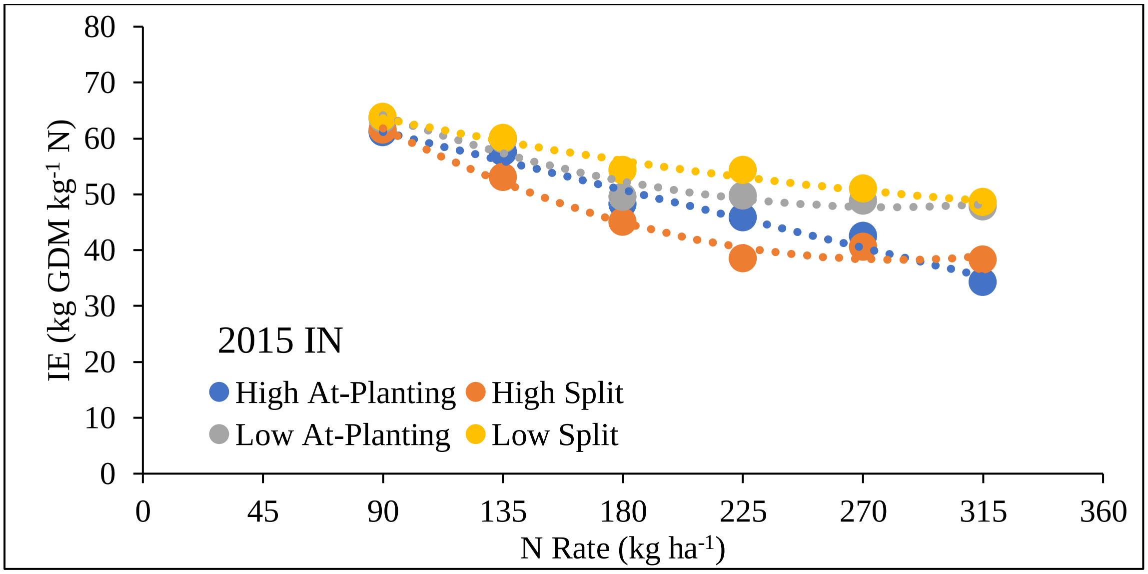

Figure 14. Internal N efficiency (IE = grain dry matter (GDM)/total plant N content at maturity) quadratic response to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) ($p \leq 0.10$), N application timing, (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage), and productivity site (low and high based on historical yield data)) at 2015 IN. Each data point represents IE at a specific N rate, productivity site, and timing averaged over four replications.

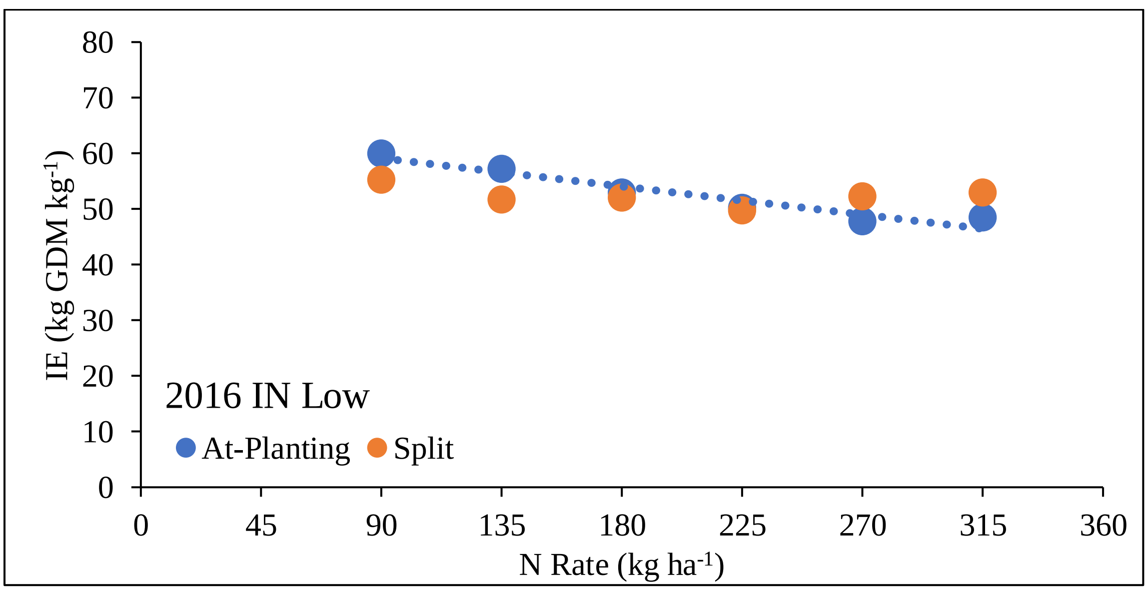

Figure 15. Internal N efficiency (IE = grain dry matter (GDM)/total plant N content at maturity) linear response ($p \leq 0.10$) to N rate and timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) in 2016 IN at the low productivity site (based on historical yield data) for N applied at-planting. Each data point represents IE at a specific N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) within N application timing averaged over four replications.

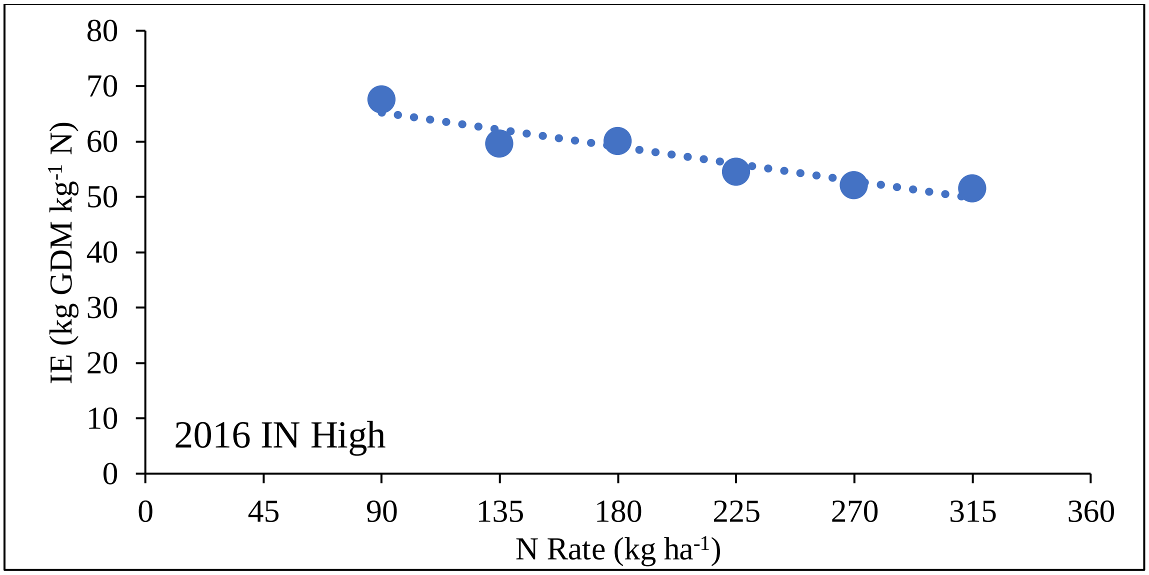

Figure 16. Internal N efficiency (IE = grain dry matter (GDM)/total plant N content at maturity) (averaged over N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) linear response ($p \leq 0.10$) to N rate (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1}) in 2016 IN at the high productivity site (based on historical yield data). Each data point represents IE at a specific N rate averaged over four replications.

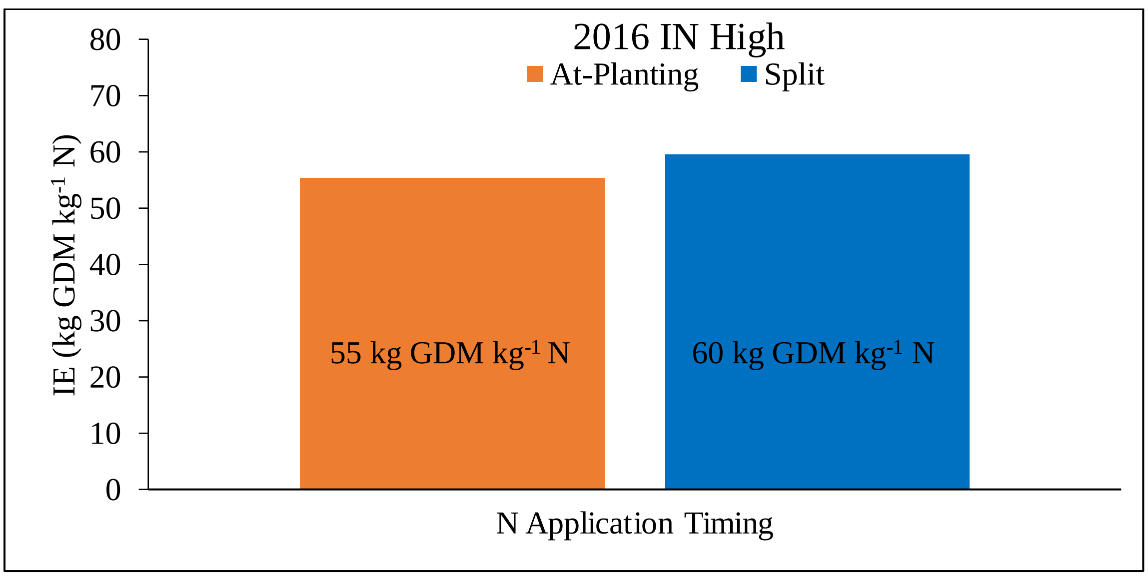

Figure 17. Internal N efficiency (IE = grain dry matter (GDM)/total plant N content at maturity) (averaged over N rates (90 to 315 kg N ha^{-1} in 45 kg N ha^{-1} increments) and productivity site (low and high based on historical yield data)) response ($p \leq 0.10$) to N application timing in 2016 IN at the high productivity site.

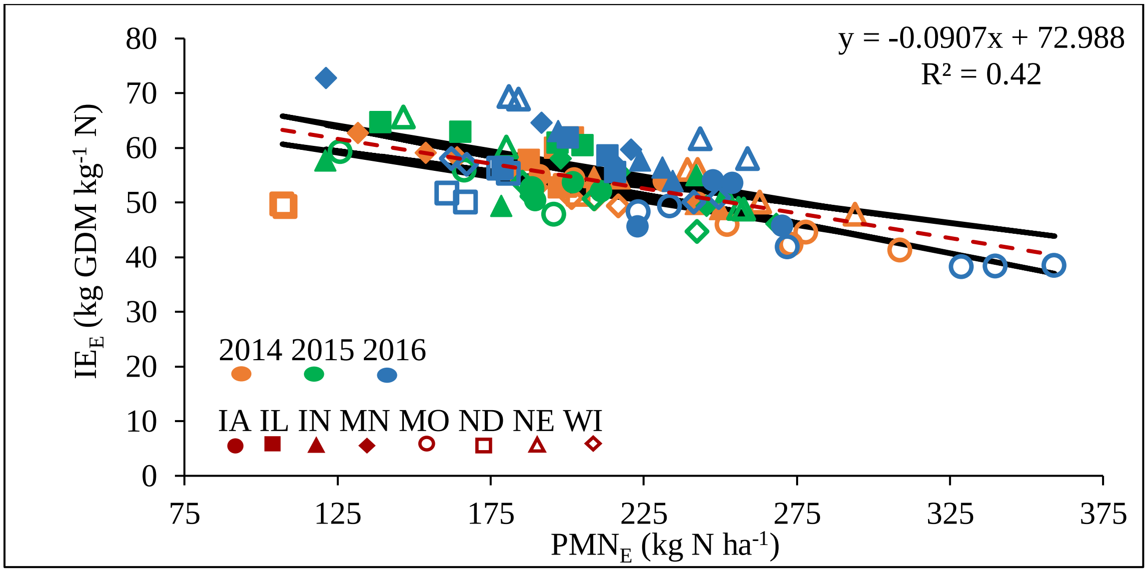

Figure 18. Physiological maturity total plant N content at the economic optimum N rate (PMN_E) linear relationship with internal N efficiency at the economic optimum N rate (IE_E) at eight state over a three year period (47 site-years) across two productivity sites (low and high based on historical yield data) and N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) ($p \leq 0.10$). Upper and lower 95% confidence intervals are shown by the solid lines.

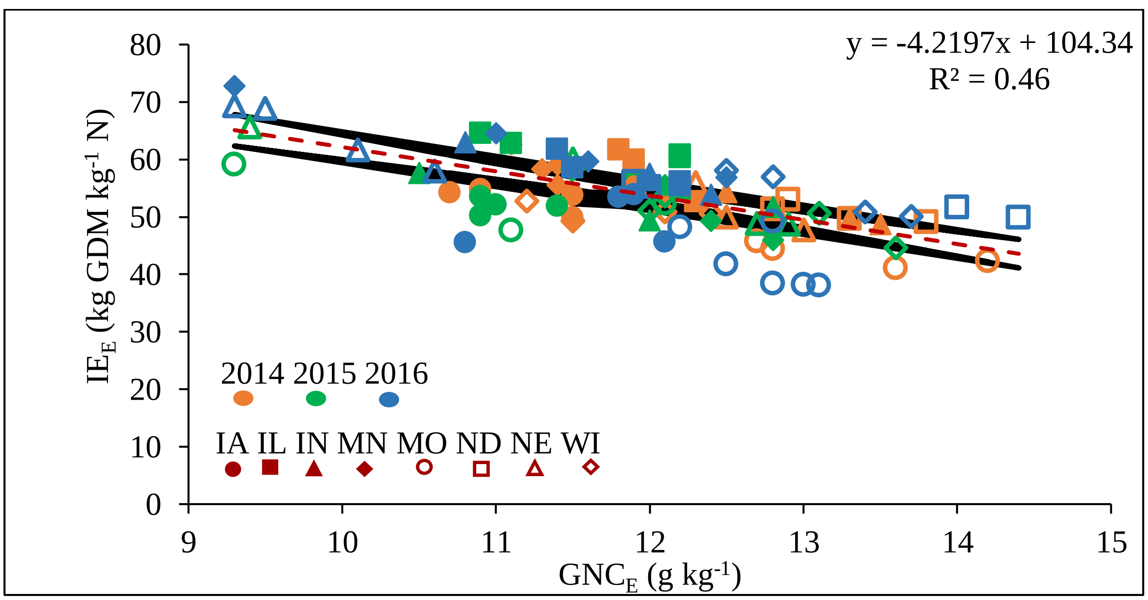

Figure 19. Grain N concentration at the economic optimum N rate (GNCE) linear relationship with internal N efficiency at the economic optimum N rate (IEE) at eight state over a three year period (47 site-years) across two productivity sites (low and high based on historical yield data) and N application timing (all 'at-planting' or 'split' with 45 kg N ha-1 at planting and the remainder at V9±1 V-stage) ($p \leq 0.10$). Upper and lower 95% confidence intervals are shown by the solid lines.

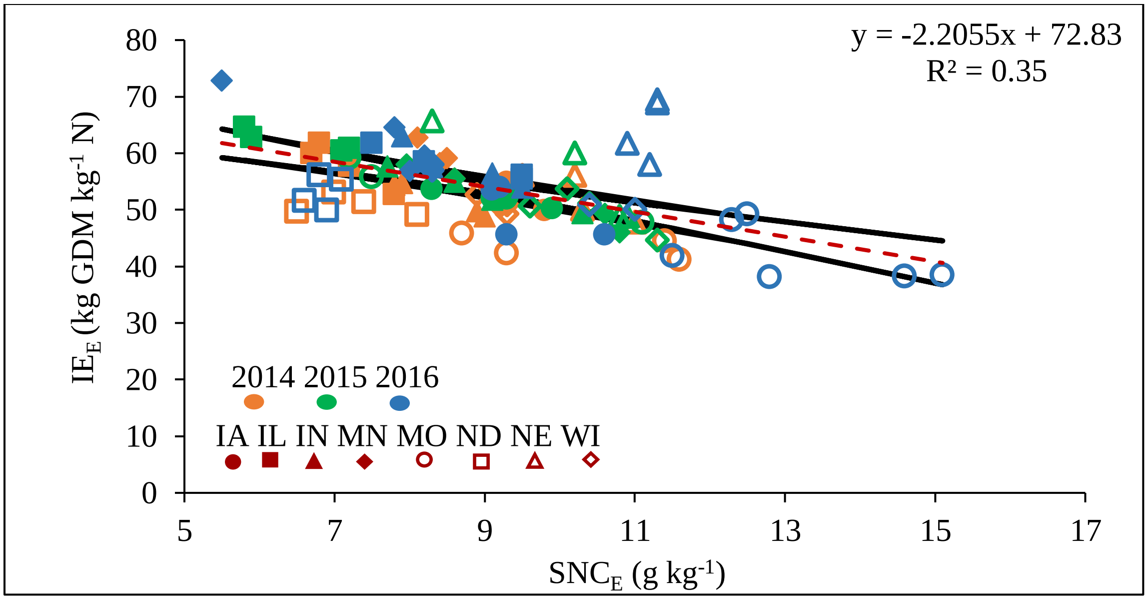

Figure 20. Stover N concentration at the economic optimum N rate (SNCE) linear relationship with internal N efficiency at the economic optimum N rate (IEE) at eight state over a three year period (47 site-years) across two productivity sites (low and high based on historical yield data) and N application timing (all 'at-planting' or 'split' with 45 kg N ha-1 at planting and the remainder at V9±1 V-stage) ($p \leq 0.10$). Upper and lower 95% confidence intervals are shown by the solid lines.

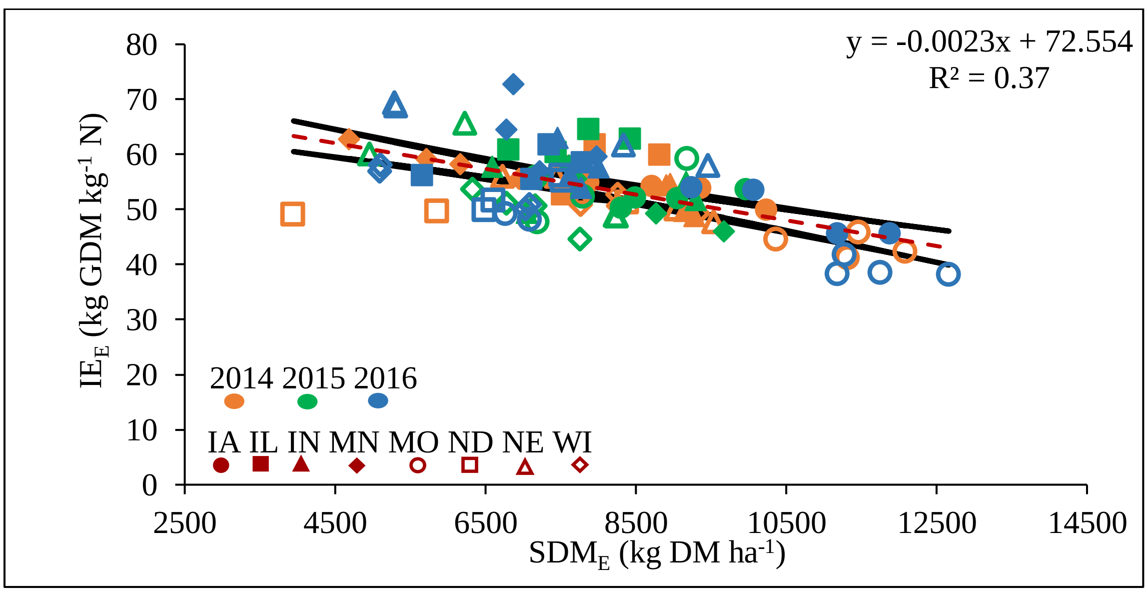

Figure 21. Stover dry matter at the economic optimum N rate (SDME) linear relationship with internal N efficiency at the economic optimum N rate (IEE) at eight state over a three year period (47 site-years) across two productivity sites (low and high based on historical yield data) and N application timing (all 'at-planting' or 'split' with 45 kg N ha-1 at planting and the remainder at V9±1 V-stage) ($p \leq 0.10$). Upper and lower 95% confidence intervals are shown by the solid lines.

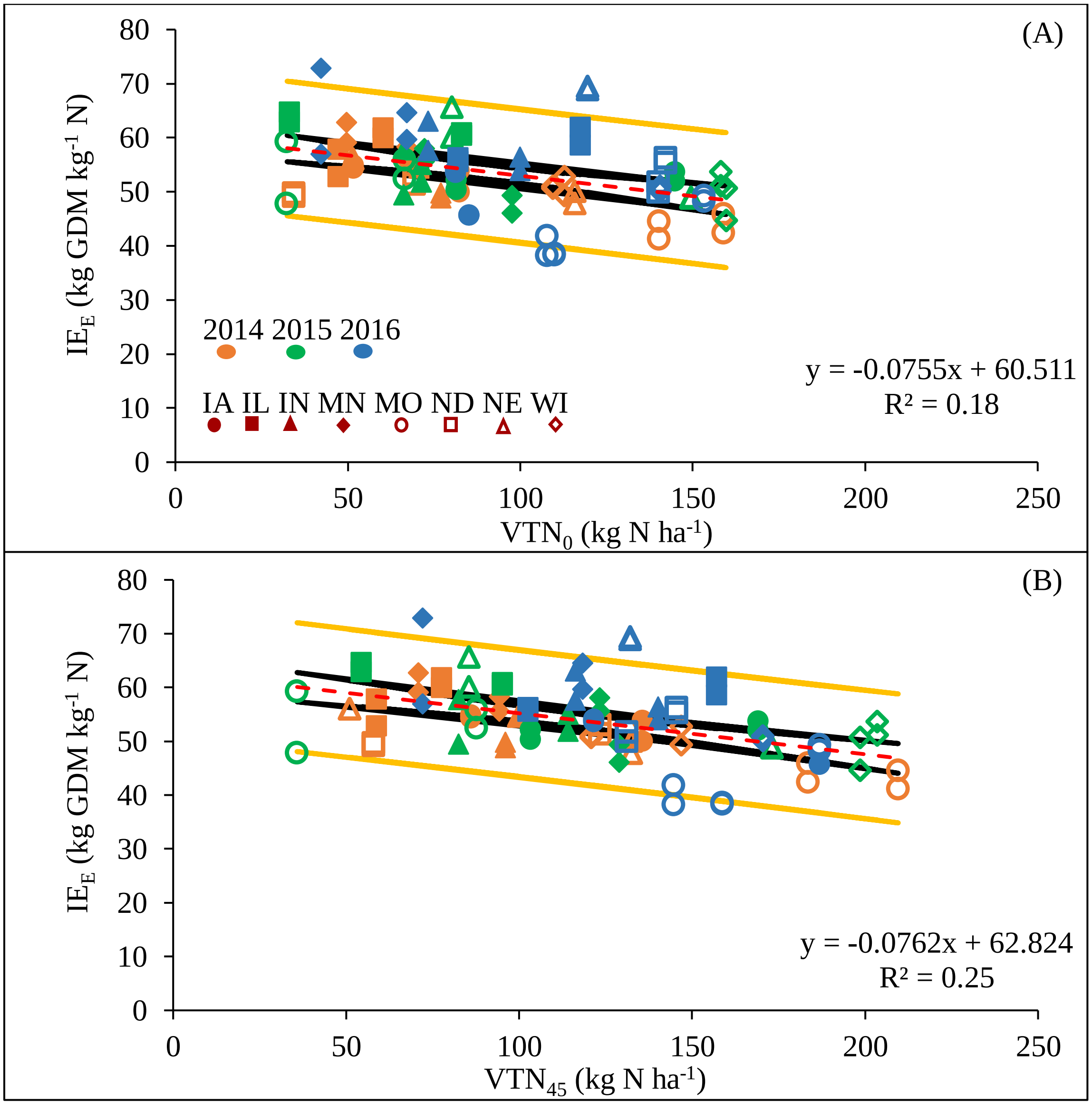

Figure 22A-B. Plant N content at tasseling at the 0 (VTN_0) (A) and 45 kg N ha^{-1} (VTN_{45}) treatments (B) relationship with internal N efficiency at the economic optimum N rate (IE_E) at eight state over a three year period (47 site-years) across two productivity sites (low and high based on historical yield data) and N application timing (all ‘at-planting’ or ‘split’ with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) ($p \leq 0.10$). Upper and lower 95% confidence intervals are shown by the solid black lines and 95% prediction intervals by the gold lines.

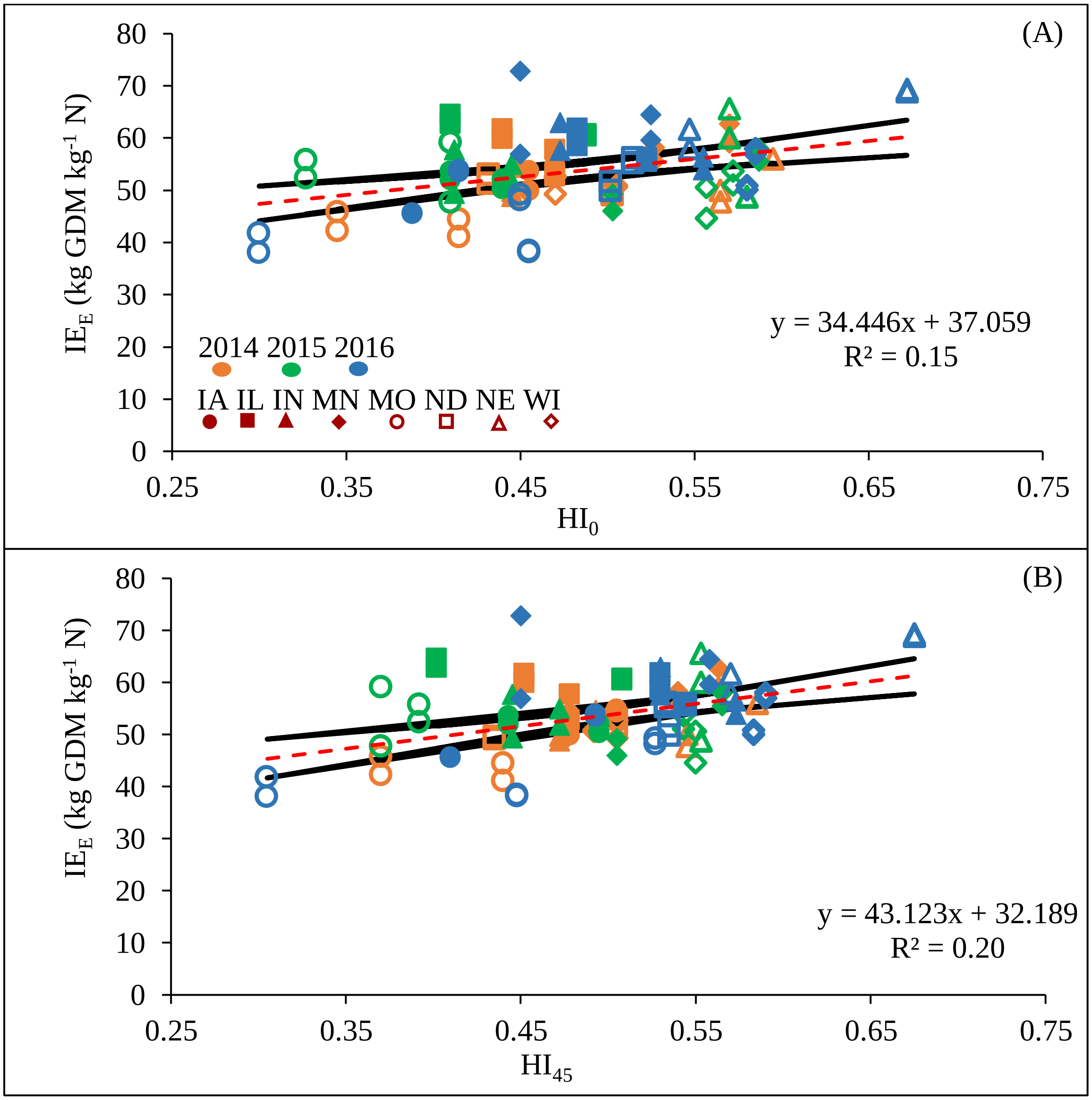

Figure 23A-B. Harvest index at 0 (HI_0) (A) and 45 kg N ha^{-1} (HI_{45}) (B) treatments relationship with internal N efficiency at the economic optimum N rate (IE_E) at eight state over a three year period (47 site-years) across two productivity sites (low and high based on historical yield data) and N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) ($p \leq 0.10$). Upper and lower 95% confidence intervals are shown by the solid lines.

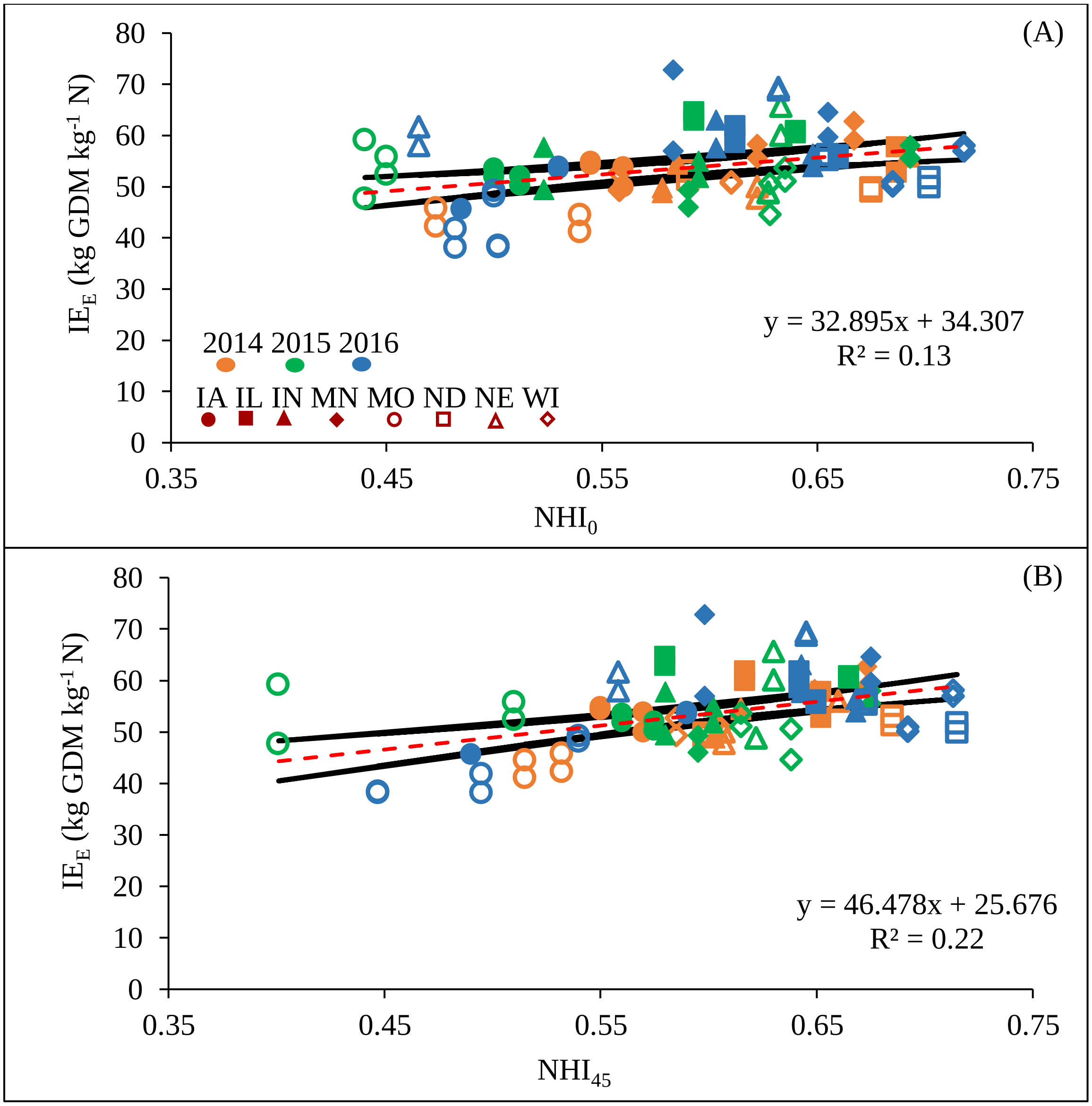

Figure 24A-B. Nitrogen harvest index at 0 (NHI_0) (A) and 45 kg N ha^{-1} (NHI_{45}) (B) treatments relationship with internal N efficiency at the economic optimum N rate (IE_E) at eight state over a three year period (47 site-years) across two productivity sites (low and high based on historical yield data) and N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage) ($p \leq 0.10$). Upper and lower 95% confidence intervals are shown by the solid lines.

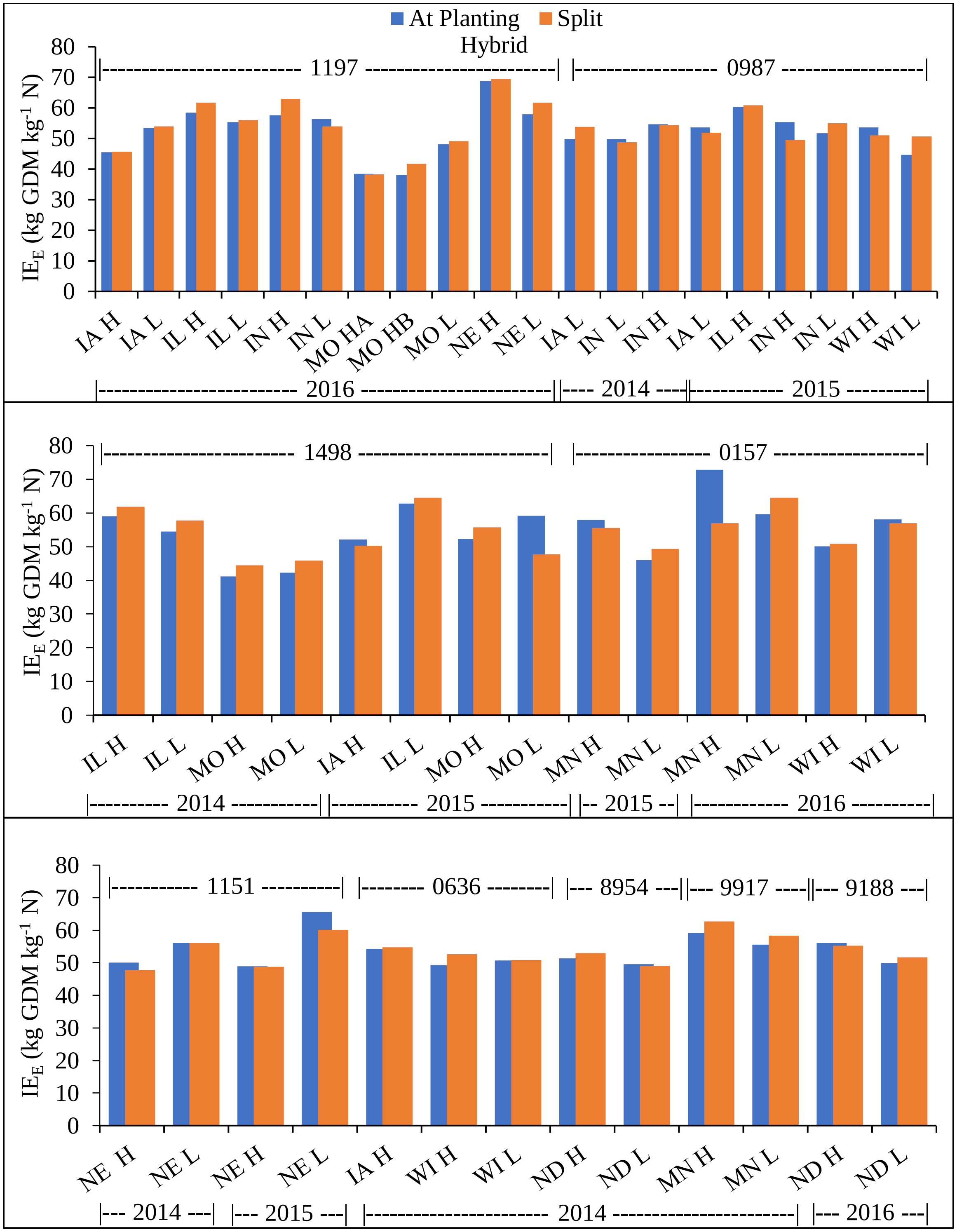

Figure 25. Internal N efficiency at the economic optimum N rate (IE$_E$) sorted by hybrid and year across eight states over a three year period (47 site-years), two productivity sites [low (L) and high (H) based on historical yield data], and N application timing (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage).

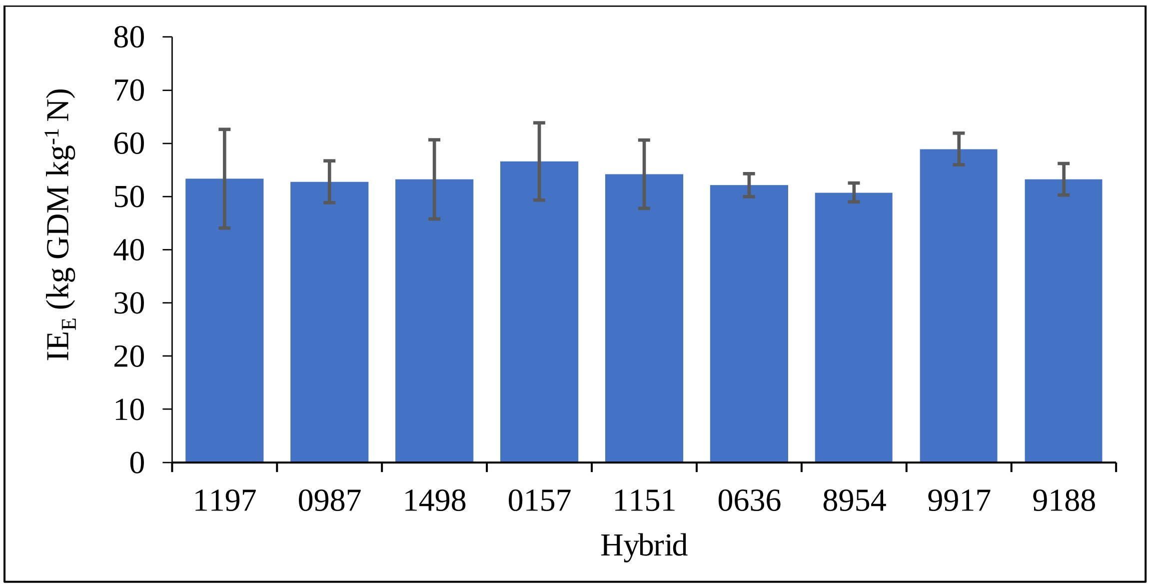

Figure 26. Mean and standard deviation of internal N efficiency at the economic optimum N rate (IE_E) within a hybrid averaged across site-years, productivity site (low and high based on historical yield data), and N application timings (all 'at-planting' or 'split' with 45 kg N ha^{-1} at planting and the remainder at V9±1 V-stage).

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