LATE-SPLIT APPLICATION OF NITROGEN ON CORN

BY

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THESIS

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ABSTRACT

The practice of applying a portion of N fertilizer during late vegetative growth of corn using high-clearance equipment has grown rapidly in the last few years, despite the absence of evidence supporting the profitability of this practice. We conducted trials at fifteen Illinois sites – six in which corn followed corn and nine in corn following soybean – in 2016-2017. In each trial, six N rates ranging from 0 to 280 kg N ha^{-1} in increments of 56 kg N ha^{-1} were assigned to main plots. Two subplot treatments were 1) each rate applied as UAN solution injected at or near the time of planting, and 2) late-split N application with a portion applied at or near planting and the remaining 56 kg N ha^{-1} hand-applied near the base of the plants at tasseling. Grain protein content, grain N content, and chlorophyll concentration measurements were collected in the trials conducted at Urbana. Grain protein and N content were found to be very similar between application timings. Chlorophyll concentrations in late-split plots were found to be lower prior to application at VT compared to plots receiving all N early, however, readings taken after application indicated plants were capable of increasing chlorophyll concentration during reproductive growth stages. Appropriate curves were fitted to the data, and economically optimum N rates (EONR), the yields at those rates (EOY), and return to nitrogen (RTN) values were calculated. EONR values ranged from 125 to 214 kg N ha^{-1} in S-C trials conducted during 2016 with EOY values ranging from 14.6 to 15.0 Mg ha^{-1}. EONR values in C-C trials conducted in 2016 ranged from 144 to 196 kg N ha^{-1} with yields at the EONR ranging from 14.3 to 14.7 Mg ha^{-1}. EONR values in the S-C trials conducted during the 2017 growing season ranged from 135 to 233 kg N ha^{-1} with EOY values ranging from 9.2 to 16.6 Mg ha^{-1}. EONR values ranged from 143 to 181 kg N ha^{-1} in the 2017 C-C trials with yields at these rates ranging from 12.9 to 14.5

Mg ha^{-1}. RTN values ranged from \$489 to \$687 ha^{-1} in S-C 2016 trials, \$690 to \$1,1129 ha^{-1} in C-C 2016 trials, \$387 to \$730 ha^{-1} in S-C 2017 trials, and \$180 to \$933 ha^{-1} in C-C 2017 trials. The average RTN over the four S-C trials conducted in 2016 was \$556 ha^{-1} when all N was applied early compared to \$560 ha^{-1} when N was late-split. The average RTN over the three C-C trials conducted in 2016 was \$978 ha^{-1} when all N was applied at planting while the average RTN when N was late-split was found to be \$983 ha^{-1}. The average RTN for 2017 S-C trials when all N was applied early was \$496 ha^{-1} compared to \$476 ha^{-1} when N was late-split. The average RTN for 2017 C-C trials was \$488 ha^{-1} when all N was applied early versus \$463 ha^{-1} when N was late-split. While the 56 kg N ha^{-1} applied late was utilized to increase yields in some cases (at the lower N rates), it did not increase the return to N, and if application costs were included, late-split N was less profitable than application of all of the N at planting. It appears that late-split application of the last increment of N is unlikely to be profitable in comparison to early application of all of the N, at least in productive soils.

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Introduction

Nitrogen (N) is widely regarded as the most important plant essential nutrient to be considered in the cultivation of non-leguminous crops. Nitrogen is the most abundant element found within plants besides those that are taken from the air or water (carbon, hydrogen, and oxygen) and is a key component in essential plant organic compounds such as proteins, nucleic acids, chlorophyll, and growth regulators. Because of this, nitrogen is most often the limiting factor in many farming systems where adequate water is available (Fernandez et al., 2009). Plant-available N exists in two forms, nitrate (NO_3^-) and ammonium (NH_4^+), which are made readily available through natural processes in quantities incapable of fulfilling the requirements for crops to produce large amounts of grain. Because of this, the use of synthetic fertilizers has been a common practice as a means to increase corn grain yields since the end of World War II.

Although the use of N fertilizers has helped increase corn grain yield performance over the last several decades, overapplication and improper management of these fertilizers have been linked to detrimental impacts on both the environment and society. Due to concerns relating to these impacts, efforts have been made within the agriculture production industry to form and implement management practices that promote the efficient use of N fertilizers in grain production and minimize the risk for loss of N fertilizers to the environment where they can have undesired effects. These management practices typically focus on the factors in which producers have control over; fertilizer application rate, timing, and placement.

An approach to reducing overapplication of N fertilizers proposed by Sawyer et al. (2006) that has been adopted in many Corn Belt states enables the use of economically optimum N rate (EONR) based on previous research, rather than tying the N rate to expected yield.

Current corn prices, the price of N, crop rotation, and location are all taken into account when determining the EONR at which producers are encouraged to apply.

Proper timing of N application is largely emphasized as a means to improve nitrogen use efficiency (NUE) and the percentage of fertilizer N recovered by the plant following application. Improving NUE and fertilizer N recovery limits the amount of soil residual N that can be lost to the environment and can be accomplished through "N synchrony"; matching the supply of fertilizer N to crop demand as crop uptake increases through vegetative growth (Cassman et al., 2002). Delaying N application until after plant emergence can improve the recovery of fertilizer N compared to application of all N at planting (Russelle et al., 1981; Russelle et al., 1983) and decrease soil residual N at low rates; however, at greater rates, the use of midseason N applications can increase fertilizer derived N within the soil which is susceptible to loss through denitrification or leaching after harvest (Jokela and Randall, 1997).

Proper placement of N fertilizer is often dependent on the time of application and form of fertilizer. Surface applications of N fertilizers, especially urea forms, are susceptible to losses through volatilization as well as runoff and can also be immobilized in scenarios where high amounts of crop residue are present (Alley et al., 2009). Applying N in a subsurface band reduces the risk for loss through these mechanisms and can increase NUE (Shapiro et al., 2016), however, nitrates within the soil can be lost through leaching or denitrification in waterlogged conditions (Randall and Vetsch, 2005).

Shanahan et al. (2008) stated "the key to optimizing tradeoffs amongst yield, profit, and environmental protection is to achieve synchrony between N supply and crop demand, while accounting for spatial and temporal variability in soil N." Eliminating or reducing fall applications and greater use of split applications rather than a single application can improve this synchronization of supply and demand (Cassman et al., 2002). Bender et al. (2013) found that modern Bt hybrids are capable of greater N uptake than their non-Bt predecessors during reproductive growth stages, possibly indicating supply of N fertilizers late in the growing season may be needed to improve this synchronization.

Adoption of spring and split N applications has been limited due to N fertilizers typically being discounted in the fall and the increased costs associated with labor and the equipment required for in season applications (Cassman et al., 2002). Use of late-split N applications has also been limited due to the fear that yield loss will occur due to N stress, especially in scenarios where application is delayed or prevented by unideal weather conditions or when crop uptake is prevented by dry conditions (Scharf et al., 2002).

Little research has been conducted on the split application of N fertilizers in rain fed corn production later than the V8 growth stage when high-clearance machinery is required for application (Scharf et al., 2002) with a majority of these studies finding conflicting results. For widespread adoption of practices that adhere to the idea of "N synchronization" to occur throughout the Corn Belt, consistent agronomic and economic advantages must be found that outweigh the risks and cost of investment associated with using the management system. This study was implemented with the intent to find whether the late-split application of N fertilizers was capable of producing greater yields when compared to a single application at or near planting or comparable yields at a reduced rate, in medium- to heavy-textured soils, such that it is economically sustainable for producers to adopt the management practice.

Literature Review

Nitrogen, and the compounds in which it occurs, are particularly difficult to manage when compared to the other plant essential nutrients that are managed by producers such as phosphorous or potassium. Nitrogen is capable of taking many forms as compounds that are both available and unavailable to the plant depending on the environment in which they occur. Understanding how nitrogen is transformed and the interactions between these different forms of the element with crops is essential for proper nutrient management (Fernandez et al., 2009).

The ultimate source of all N used by plants is N_2, which constitutes 78-79% of the earth's atmosphere. Unfortunately, corn plants cannot metabolize N_2 directly into protein. N_2 must first be converted to an available form for corn uptake by non-symbiotic soil microorganisms, atmospheric electrical discharges forming N oxides, or the manufacture of synthetic N fertilizers (Havlin et al., 2005).

The first step in the nitrogen cycle involves N in plant and animal residues (organic matter) and N derived from the atmosphere through electrical, combustion, and industrial processes (N_2 is combined with H_2 or O_2) being added to the soil. Most (>90%) of the N in soils is contained in organic matter, which is relatively stable and not directly available to plants. Organic N therefore must be mineralized to NH_4^+ by soil microorganisms. NH_4^+ is a plant available form of N and a portion of this mineralized form is absorbed by plant roots (Havlin et al., 2005). Although this transformation of organic N by microorganisms plays a vital role in the N cycle, it is often a process that occurs at a variable rate depending on management practices and environmental conditions which releases only a small amount (2-3%) of N that is required to produce a quality crop on a yearly basis (Below, 2002). Much of the remaining NH_4^+ located within the soil is then converted from NH_4^+ to NO_3^- by nitrifying bacteria in a process called nitrification. A small portion of NH_4^+ can also be converted to NH_3 through a process called volatilization which is then reintroduced to the atmosphere. NO_3^- is also a plant available form of N which again a portion is adsorbed by the plant roots. The remaining NO_3^- within the soil then faces one of two fates. This form can be lost to groundwater or drainage systems through leaching. The alternative is that NO_3^- is converted by denitrifying bacteria to N_2O and NO forms that escape into the atmosphere completing the cycle (Havlin et al., 2005).

The loss of plant available NO_3^- from the soil not only limits the efficiency at which applied N fertilizers are used in crop production, but can also have detrimental impacts within society and the environment. Rabalais et al. (1996) identified excessive NO_3^- loading within the Mississippi River as a leading cause for the hypoxic zone within the Gulf of Mexico. Hypoxia occurs when the levels of dissolved oxygen within water fall below 2 mg/L and can no longer sustain normal levels of plant and animal life. Hypoxia within the Gulf of Mexico is caused by large phytoplankton algae blooms, promoted by the increased presence of plant essential nutrients from the Mississippi River, which eventually lead to the depletion of dissolved oxygen through the process of decomposition. This occurrence can heavily affect commercial fishing harvests and the health of the impacted ecosystem (National Oceanic and Atmospheric Administration, 2000).

The presence of nitrates and nitrites in drinking water has become a concern due to possible health implications thought to be caused by consuming these compounds in high concentrations. Because of this the U.S. EPA has set a maximum contaminant level (MCL) for drinking water of 10 mg/L which is often exceeded within the Midwest Corn Belt. To maintain standards within these limits, many areas that depend on surface water as a drinking water supply have installed denitrification systems to remove excessive water nitrates, causing increased expense for water treatment (Jaynes and Colvin, 2006; cited Jaynes et al., 1999; Mitchel et al., 2000; Dinnes et al., 2002).

Non-leguminous plants such as corn require a relatively large amount of N (1.5-5% of plant dry matter), in comparison to other mineral nutrients, as an essential component of numerous organic compounds. These compounds include proteins, nucleic acids, chlorophyll, and growth regulators, all of which play an essential role in the growth and development of the plant. The N required for the assimilation of these organic compounds is acquired largely from the soil through uptake by the root system. The uptake of the plant available inorganic N compounds NO_3^- and NH_4^+ is generally considered to be a metabolic process and occurs at a varying rate dependent on the internal concentration of the compounds within the plant as well as environmental factors such as temperature and pH (Below, 2002).

After absorption, inorganic N must be assimilated into organic forms, typically amino acids, to be used by the plant. NH_4^+ is toxic to plant tissues at relatively low concentrations and therefore is assimilated rapidly within the root and transported throughout the plant as organic compounds. NO_3^- is capable of being stored or assimilated within the roots as well as being transported to the shoot where it is either stored or assimilated. Stored NO_3^- plays an important role as a source of N that can be assimilated for use when all external N has been depleted (Below, 2002).

Sufficient accumulation of N plays an essential role in determining the growth, development, and productivity of plants. Approximately 60% of the N present in leaf tissue is associated with proteins in the chloroplasts of the plant. The accumulation of dry matter in cereal grains is largely determined by the rate of photosynthesis from vegetative growth through grain fill and therefore is dependent upon the availability of N to maintain chlorophyll levels required for photosynthesis. In cases when no other limiting factors are present, it has been observed that an increase in the supply of plant available nitrogen increased the chlorophyll concentration and growth of leaves, the key factors in determining the photosynthetic capacity of the plant (Below, 2002). In contrast, nitrogen deficiency in corn can cause a delay in the emergence of new leaves, significantly reduce leaf area, and delay tasseling, anthesis, and silking (Uhart and Andrade, 1995).

Although nutrient management is a complex process, improving our understanding of uptake timing and rates, partitioning, and remobilization of nutrients by corn plants provides opportunities to optimize fertilizer rates, sources, and application timings (Bender et al., 2013). The accumulation of N by the plant throughout the growing season typically begins slowly due to small amount required by the limited biomass of the plant. As the plant advances in vegetative growth there is a rapid, nearly linear increase in accumulation up to the late stages of vegetative growth where the rate of accumulation decreases and continues through grain fill. In general, the two periods in which N accumulation occurs most rapidly coincide with the late vegetative growth stages of plant as well as the onset of grain fill. In most cases, a majority of the N accumulated by cereal plants occurs during vegetative growth with research indicating 75% or more having been accumulated by anthesis (Below, 2002). Despite a majority of N uptake occurring before anthesis, it was noted by Hanway (1962) that adequate supply of N for the continued accumulation by the plants later in the season is essential to prevent excessive loss through translocation of N from the leaves which would result in premature death of some of the leaves, limiting the photosynthetic capacity of plants during leading up to and through grain fill.

It has been reported that modern hybrids possess the capability for greater N uptake during reproductive growth stages than hybrids used in the past. In a study examining the nutrient accumulation of modern hybrids with transgenic insect protection from corn rootworm (Bt) in comparison with non-Bt hybrids, Bender et al. (2013) found that yield responsive Bt hybrids acquired 31% more N during grain fill than their non-Bt counterparts. It was observed that this difference primarily occurred after the R4 growth stage when biomass accumulation was approximately twofold greater in insect-protected hybrids. The indication that modern hybrids are capable of greater N uptake during late stages of development may imply there is a requirement for sufficient plant available N during this period to ensure maximum productivity leading to maturity.

Determining the proper rate of N fertilizer application is a crucial decision for corn producers in order to maximize economic gain while remaining responsible stewards of the land. The nitrogen fertilizer required to produce a high yielding crop can vary substantially from location to location and even within the same field. A common practice throughout the Midwest is to apply the same rate of N fertilizer across whole fields and in some cases use the same rate on all fields used for corn production. Furthermore, overapplication of N fertilizers is not all together uncommon due to the economic incentive to err more frequently in that direction: The cost of unneeded N fertilizers in areas of overapplication is less than the cost of lost yield potential in areas of underapplication (Scharf et al. 2005). While this approach simplifies decision making for farmers, it creates the potential for over application of N fertilizers, especially on marginal ground incapable of producing the biomass required to take up the fertilizer applied or on coarse textured soils that are prone to nitrogen leaching. Overapplication of N fertilizers dramatically increases soil residual N concentrations after harvest and during the following spring which can lead to contamination of ground and surface waters in humid regions of the United States. The implementation of accurate fertilizer N rates can reduce soil residual N levels, minimizing the opportunity for N loss to the environment and increasing the efficiency at which the fertilizer is used in crop production (Lory and Scharf, 2003).

For many years N rate recommendations throughout the Midwest were based on the expected yield for a particular field by examining the production history of the field and the amount of N required to meet the expected yield. This N fertilizer recommendation is calculated by determining the amount of N removed by the crop at the expected yield and then subtracting or “crediting” any N added to the soil through mineralization, manure application, or biological fixation from previous legume crop production resulting in the amount of fertilizer N that must be added to meet the requirements of the expected crop yield (Stanford, 1973). While this simplified approach may be intuitively appealing, it is not without its flaws. Corn yields are often highly variable on a year to year basis and are largely dependent on weather conditions as well as the management practices implemented in production such as tillage, crop rotation, hybrid selection, and disease, weed, and pest pressure. The use of this recommendation system is largely dependent on consistent yield levels from year to year, allowing the potential for over application of N fertilizers in environments that limit crop production, and concentrates largely on the “yield goal” for a particular piece of land rather than the economic potential of the production system where a producer’s true priority lies.

A second method of determining N fertilizer recommendations has been adopted in several Corn Belt states in recent years that emphasizes the maximum return to nitrogen (MRTN) or the N rate where the economic return to N application is greatest. Using data from replicated N rate trials within a given region, rotation history, and current commodity and fertilizer product pricing, researchers are able to calculate the predicted corn yield response to N fertilizer which can be used to determine the economic optimum nitrogen rate (EONR) or the point where the last increment of N returns a grain yield increase large enough to pay for that N (Sawyer et al. 2006). Gross return of a specific rate trial within a regional database is calculated as the estimated yield at each N rate minus the yield where no N was applied multiplied by the price of corn grain and is represented as ΔY (Morris et al., 2018). Return to N is calculated by subtracting the cost of N (N rate x price of N) from the gross return or ΔY. (Morris et al.) The overall RTN for a specific region is the average of all calculated RTN values across trials at each rate (Morris et al.). The curve representative of the overall RTN forms as a quadratic + plateau, where the predicted MRTN of a region is where the slope of the curve is equal to zero (Morris et al.). In the analysis of two historical databases over three geographic locations, Kachanoski et al. (1996) found that ΔY based on the difference between maximum yield and the yield within plots receiving no N fertilizer accounted for 50-77% of the variability of MRTN values. The ΔY based on the difference between economic yield and plots receiving no N was found to account for 50-75% of the variability of MRTN values. Based on these findings, it was concluded by the researchers that both ΔY values may be reasonable predictive indexes for the MRTN. By providing a method for developing N rate guidelines directly from response databases on a local or regional basis, the MRTN approach is capable of providing more region-specific recommendations that focus on the maximum economic return for producers (Sawyer et al. 2006). Furthermore, this system allows growers and their advisors to more accurately predict the economic outcome of the crop production system due to is capability to make adjustments based on site history, N price, and grain price (Sawyer et al. 2006).

While choosing the appropriate rate at which to apply N is an essential component in sound nutrient management, proper placement of the fertilizer is equally as crucial. Broadly, three objectives are involved in fertilizer placement. These are to result in efficient fertilizer use by the plant, to prevent fertilizer salt injury to plants, and to provide an economical and convenient operation (Randall et al., 1985). While there are many options available when choosing a delivery system, fertilizer applications can be divided into three general categories by placement; soil subsurface application, soil surface application, and foliar application. Leaching, denitrification, immobilization, and NH_3 volatilization are the processes known to be of practical significance in lowering availability of N to plants (Bock, 1984). Each of these three general categories of fertilizer placement can be subject to one or more of these processes, and may possess advantages in comparison with the others which must be implemented properly to increase the efficiency at which fertilizers are utilized.

Subsurface application of N fertilizers such as anhydrous ammonia (NH_3), urea [$CO(NH_2)_2$] and urea-ammonium nitrate solution is a common practice in cereal crop cultivation (Havlin et al. 2005). Anhydrous ammonia is applied as a pressurized liquid that immediately vaporizes as the liquid emerges from the applicator and for this reason requires subsurface placement in order to prevent loss of the vapor to the atmosphere (Randall et al., 1985). Subsurface application of N fertilizers can help avoid immobilization by soil microorganisms in high residue scenarios and minimize the risk for loss by volatilization and runoff in comparison to broadcast surface applications (Shapiro et al., 2016). Although subsurface applications can reduce the risk for loss through these mechanisms, soil nitrate is subject to loss through denitrification or leaching in wet soils (Randall and Vetsch, 2005). Fall subsurface application further increases the risk of the loss through these processes due to the prolonged time the fertilizer remains within the soil prior to the beginning of plant uptake (Randall and Vetsch, 2005). Spring subsurface applications can mitigate this loss potential, however salt injury can also occur if N fertilizers are placed in close proximity to germinating seedlings (Alley et al., 2009).

Surface applied N fertilizers are subject to immobilization by soil microbes in fields where high amounts of crop residue are present and can also be lost to the environment in surface runoff (Shapiro et al. 2016). Additionally, urea or fertilizers containing urea such as UAN, are particularly susceptible to loss through volatilization when not incorporated (Fox et al., 1986). When urea fertilizers are applied to the surface without incorporation or adequate precipitation to move the fertilizer into the soil, losses of fertilizer N as NH_3 can exceed 40% and generally greater with increasing temperature, soil pH, and surface residue (Raun and Johnson, 1999; cited Fowler and Brydon, 1989; Hargrove et al., 1977). Surface applications using high-clearance machinery or aerial broadcast applicators are typically required when timely sidedress applications are prevented or when N stress becomes apparent later in the season when subsurface applications are no longer an option (Jaynes and Colvin, 2006; Nelson et al., 2011). Nelson et al. found that applying UAN between rows when a “rescue application” was necessary was an excellent treatment option despite the possibility of N immobilization or volatilization and reduced crop leaf injury compared to broadcast applications.

Foliar N applications have been viewed as a possible means of supplying supplemental N to crops during late vegetative growth to replace depleted nutrient levels in plant leaf tissue and quickly correct nutrient deficiencies in plants, however research of these applications has resulted in inconsistent and often conflicting results (Randall et al., 1985). Research on foliar applications with the major elements N, P, K, and S for field grain crops has shown that very significant yield increases sometimes result from foliar applications made during the seed-filling period. Although these yield increases have not been consistent, decreases in nutrient concentrations are commonly observed in leaves of grain crops during the seed-filling period, and foliar application of nutrients during this period does offer some potential for improving yields (Randall et al., 1985). In contrast, Tomar et al. (1988) found that foliar N applications did not improve corn grain yield and possessed very limited potential for doing so. Adoption of this practice has been limited largely due the risks and economics associated. Overapplication of foliar fertilizers containing urea can cause severe leaf damage that can lower the photosynthetic capacity of plants. Additionally, to limit the risk of damaging leaf tissues while maximizing uptake of foliar applied N, corn plants would need to be applied with foliar N one to two times per week which is not economically feasible (Keeney, 1982). At the present time, foliar applications are not a recommended best management practice.

Choosing the appropriate time at which to apply N fertilizers is an additional challenge corn producers face when composing a nutrient management strategy. Application of N fertilizers when plant demand for uptake is present is the most logical approach to increasing N fertilizer efficiency (Keeney, 1982) which is essential in maximizing economic return to the grower, minimizing the potential impact on water quality, and reducing the total energy required for manufacture of N (Jokela and Randall, 1989). Timely application of nutrient fertilizers when crop demand exists is also essential in effectively minimizing nutrient stress, especially in high-yielding conditions (Bender et al. 2013).

Many producers throughout the Midwest choose to apply N fertilizer during the fall following harvest due to better distribution of labor and equipment demands, ample time for application that otherwise would be needed during the spring when planting also occurs, lower N fertilizer costs in some years, and favorable weather conditions for application (Randall and Vetsch, 2005). While fall application can simplify the logistics and in same case lower production costs, it also increases the potential for N fertilizers to move off-site through denitrification or leaching when winter snows thaw or during times of heavy rainfall which are not altogether uncommon during the winter months in the Midwest. Agronomically, applications of all N fertilizer in the fall may also limit yield potential. In a five-year study in Minnesota, Randall and Mulla (2001) found that corn yields in plots receiving all N fertilizer in the late fall (November) produced 8 percent lower yields while losing 36 percent more nitrate through tile lines compared to plots receiving spring-applied N.

Spring N applications reduce the timespan in which N fertilizers are present within the soil before plant uptake begins, therefore reducing the potential for fertilizers to move off-target and are a favorable option with consideration to possible environmental impacts as well as the containment of N fertilizers within the intended area of application where their use can be optimized by the crop. Spring applications can however have their limitations. Timely planting of crops is also essential when pursuing the cultivation of a high yielding crop, because of this if a producer wishes to separate spring N application from herbicide application, the window of opportunity for application becomes very narrow (Randall and Sawyer, 2008). Additionally, spring is typically a time of frequent rainfall which can limit the time in which field conditions are appropriate for producers to both plant their crop and apply fertilizers.

Delaying N fertilizer applications can help avoid wet field conditions that typically occur during the spring, allow for application after planting is finished when time is no longer constrained, and also allow for the assessment and correction of N loss to meet plant demand in years where high amounts of loss are suspected (Scharf et al., 2002). Additionally, it has been observed that delayed applications of N fertilizers can increase plant recovery of fertilizer derived N when compared to applications made at planting, indicating a greater use efficiency of the applied fertilizer (Jokela and Randall, 1997). It has also been found that delaying a portion or all N fertilizer applications can allow for more precise diagnosis of crop nutrient requirements through spring soil testing (Blackmer et al., 1989) or chlorophyll meter readings (Varvel et al., 1997). Reported research on delayed N applications and their effects on corn yield however is often conflicting and research conducted using N applications made during the late vegetative growth stages of the crop is limited. Results from these studies rarely share similar application timings and often times find varying results as to when the delayed application of N fertilizers begins to limit or decrease corn grain yields.

In the analysis of 28 N-timing experiments, Scharf et al. (2002) found no evidence of yield reduction when application of all N fertilizer was delayed as late as V11, evidence of small yield reductions (3%) when application of all N was delayed until V12 to V16, and moderate yield reductions (15%) when application of all N was delayed until silking.

Walsh et al. (2012) found there was no significant decrease in grain yield associated with delaying sidedress N application until the V10 growth stage and VT when preplant N was applied, however, delaying N fertilizer applications until later growth stages (V10-VT) generally resulted in decreased grain yields (in six of nine site-years) when no preplant N was applied.

Jaynes (2013) conducted a study in central Iowa comparing sidedress N applications made with all N applied at V2, split equally between V2 and V6, and split equally between V2 and V12. Reported findings from the study indicate no significant differences in grain yield or subsurface tiling nitrate discharge between application timing treatments, indicating no yield limitation was caused by delaying application of a portion of N as late as V12.

In an earlier study also conducted in central Iowa, Jaynes and Colvin (2006) found that midseason application (V16) of liquid UAN yielded significantly less corn grain yield than if the same amount of N was applied all post emergence (V1-V3). When insufficient N was present, however, the midseason application of N increased yield as much as 29%. Furthermore, it was reported that nitrate losses in tile drainage were increased by the midseason application and when compared across the four-year study, were significantly greater than losses from when the same amount of N fertilizer was applied in one application after emergence. It was then concluded by the researchers that a late-split application of fertilizer N may be a possible solution in scenarios where large amounts of N have been lost throughout the growing season, however the practice should not be considered a best management practice for water quality.

Mueller et al. (2017) conducted a three-year study investigating the effects of late-split N applications on the nitrogen fertilizer recovery efficiency and N accumulation and partitioning of corn between two modern hybrids (2012 and 2014) and two older hybrids (1991 and 1995). Plots received either all N in a single application at V3-V4 or 45 kg N ha^{-1} was withheld and applied at V12-V14. In 2014 and 2015 rates included 0, 155, 200, and 245 kg N ha^{-1} and a rate of 110 kg N ha^{-1} was added to the study during the 2016 growing season. It was observed that a supplemental application of 45 kg N ha^{-1} at V12-V14 increased nitrogen fertilizer recovery efficiency through higher post-silking uptake as well as whole plant N accumulation at R6 when compared to a single application of all N at V3-V4. These increases were rarely associated with increased grain yield. The modern hybrids used in the study did consistently yield more than the older hybrids used, but there was very little evidence of greater responses of modern hybrids to N rate or timing for grain yield, R6 biomass accumulation, or R6 N content. This study found that corn grain yield is not sensitive to the timing of supplemental late-split applications when N is nonlimiting. It was noted by the researchers that increasing nitrogen fertilizer recovery efficiency through this management practice has the potential to reduce soil residual N that can be lost to the environment following harvest.

Materials and Methods

A total of fifteen field research trials were conducted during the 2016 and 2017 growing seasons. Trials in which corn followed soybean were conducted near DeKalb, Monmouth, Perry, and Urbana, Illinois, and trials in which corn followed corn were established at the Monmouth, Perry, and Urbana sites. In 2017, an additional corn following soybean trial was conducted near Neoga, Illinois. Soil organic matter percentages were taken from the most recent soil testing results recorded and can be seen in Table 1 below. The monthly total rainfall for each site during the 2016 and 2017 growing seasons can be found in Table 2 along with the state 30-year average precipitation by month.

Trials were laid out as a split-plot arrangement in a randomized complete block design with four replications. Nitrogen rates of 0, 56, 112, 168, 224 and 280 kg N ha^{-1} were assigned to main plots. Application timing assigned to subplots were: 1) all N fertilizer was applied at planting or near the time of planting; and 2) the assigned N rate less 56 kg N ha^{-1} was applied at the same time as the rates in #1, and then the remaining 56 kg N ha^{-1} was applied at the VT growth stage. The N source in all cases was urea-ammonium nitrate (UAN) solution with 28% or 32% N by weight. Applications made at or near planting were injected beneath the soil surface between rows. Applications at VT were made using a hand-boom to apply UAN solution near the base of the plants. Experimental units consisted of four 76-cm rows with lengths varying from 21.3 to 61 meters in 2016 and 24.4 to 61 meters 2017.

The center two rows of each plot were harvested with a plot combine and grain yields were moisture corrected to 150g kg^{-1} water. A sample was taken from the harvested grain in each plot of the trials conducted at Urbana in 2016 and 2017. Grain protein content values (g protein/100 g grain) were measured using a FOSS Infratec 1241 Grain Analyzer. Grain protein contents were then converted to total grain N content (kg N ha^{-1}) by dividing by the constant 6.25 (g protein/g N) (Jones, 1931) and multiplying by grain yield (kg ha^{-1}). Grain yields were corrected to 0% moisture to perform this calculation due to grain protein content from the grain analysis being expressed on a 0% moisture basis.

Chlorophyll concentration readings were taken using a SPAD meter in 2016 and 2017 in all four trials conducted in Urbana. Readings were taken in all plots before application at VT and again at R2-R3 to find if leaf chlorophyll recovered following late-split N application and if the recovery matched that of plots receiving all N early.

Statistical analyses were performed using the SAS statistical analysis software package (SAS Institute Inc.). Years, locations, N rates, and N application timing were designated as fixed, with reps and all interactions associated with reps designated as random. Data were analyzed using PROC GLIMMIX of SAS to obtain the least square means of grain yields of plots at each nitrogen rate to determine whether a significant difference in grain yield was observed between the plots receiving all N early and plots that were treated with late-split N at $\alpha = 0.10$. Data were fitted to a quadratic plus plateau function using PROC NLIN of SAS, and quadratic coefficients were used to calculate the economically optimum nitrogen rate (EONR), the yield at that rate (EOY), and the return to nitrogen (RTN) values. The EONR values were calculated as the point at which the slope of the quadratic function was equal to the ratio of input price (cost of N fertilizer) to output price (corn grain price.) Prices used were \$0.88 kg N^{-1} and \$157 Mg^{-1} for a ratio (slope of cost line) of 0.0056 kg N/Mg grain. Predicted yield at the EONR (EOY) was calculated, and RTN was calculated as follows:

$$\text{RTN (\$/ha)} = \Delta Y \text{ (EOY – yield at N=0) x \$/Mg grain – EONR x \$kg/N}$$

Results and Discussion

Precipitation during the 2016 growing season was very well distributed at the trial sites (Table 2). Growing conditions were very favorable throughout the state, with a state average corn yield of 12.4 Mg ha^{-1}. Heavy rainfall in late April and early May in 2017 (Table 2) was followed by favorable weather during the months of June and July, and drier conditions during August and September (Table 2). The state average corn yield was 12.6 Mg ha^{-1} in 2017.

Weather conditions in 2016 were favorable at the DeKalb C-S trial location, with higher than average precipitation occurring during the month of May and consistent rainfall occurring from June to August (Table 2). Yield averages ranged from 10.2 Mg ha^{-1} in plots receiving no N fertilizer to 15.1 Mg ha^{-1} in plots receiving 280 Mg ha^{-1} early (Figure 1). Response to N was very similar for both application timings (Figure 1). Late-split application of 56 kg N ha^{-1} at VT resulted in a significantly higher yield compared to application of 56 kg N ha^{-1} applied early with yield averages of 12.5 Mg ha^{-1} and 11.6 Mg ha^{-1}, respectively (Figure 1). The EONR for early N application was 214 kg N ha^{-1} with an estimated yield of 14.8 Mg ha^{-1} (Table 3). The EONR for late-split application of N was 183 kg N ha^{-1} with an estimated yield of 14.5 Mg ha^{-1} (Table 3). A greater RTN at the EONR was observed when all N was applied early rather than late-split, with values of \$530 ha^{-1} and \$511 ha^{-1}, respectively (Table 3).

Precipitation fluctuated more during the 2017 growing season and total rainfall was much less than in 2016 in DeKalb (Table 2). Yield averages in the C-S trial ranged from 10.9 Mg/ha in plots receiving no N fertilizer to 16.7 Mg ha^{-1} in plots receiving 168 kg N ha^{-1} applied early (Figure 2). A much greater response to N was observed when all N was applied early compared to late-split at rates ranging from 56 to 168 kg N ha^{-1} with similar responses between application timings at rates >168 kg N ha^{-1} (Figure 2). Early application of N fertilizer resulted in significantly greater yields at rates of 112 kg N ha^{-1} and 168 kg N ha^{-1}. Plots receiving 112 kg N ha^{-1} early yielded 15.9 Mg ha^{-1} on average while plots receiving late-split N at this rate produced an average yield of 14.4 Mg ha^{-1} (Figure 2). Application of 168 kg N ha^{-1} early resulted in an average yield of 16.7 Mg ha^{-1} with plots receiving late-split N at this rate yielding an average of 16.0 Mg ha^{-1} (Figure 2). The EONR for early N application was 170 kg N ha^{-1} with an estimated yield of 16.5 Mg ha^{-1} (Table 3). The EONR for late-split application of N was 233 kg N ha^{-1} with an estimated yield of 16.6 Mg ha^{-1}. Early application of all N resulted in a greater RTN at the EONR at \$730 ha^{-1} compared to \$694 ha^{-1} when N was late-split (Table 3).

Rainfall during 2016 was consistent in Monmouth with greater than average precipitation occurring from June to August (Table 2). Yield averages in the C-S trial ranged from 10.9 Mg ha^{-1} in plots receiving no N fertilizer to 15.2 Mg ha^{-1} in plots receiving late-split N at a rate of 224 kg N ha^{-1} (Figure 3). Response to N was nearly identical between application timings and no significant yield differences were observed between early and late-split applications at any rate (Figure 3). The EONR for early N application was 126 kg N ha^{-1} with an estimated yield of 14.7 Mg ha^{-1}. Late-split application of N resulted in an EONR of 146 kg N ha^{-1} and estimated yield of 15.0 Mg ha^{-1} (Table 3). A greater RTN at the EONR was observed with late-split application of N at \$515 ha^{-1} compared to \$499 ha^{-1} when all N was applied early (Table 3). Yield averages in the C-C trial ranged from 9.2 Mg ha^{-1} in plots receiving no N fertilizer to 14.8 Mg ha^{-1} when 280 kg N ha^{-1} was applied early (Figure 4). A greater response to N was observed at low rates when application was late-split with responses between applications timings being very similar at rates ≥165 kg N ha^{-1} (Figure 4). A significantly greater yield of 12.5 Mg ha^{-1} was observed when 56 kg N ha^{-1} was applied at VT compared to a yield of 11.8 Mg ha^{-1} when 56 kg N ha^{-1} was applied early (Figure 4). The EONR for early N application was 170 kg N ha^{-1} with an estimated yield of 14.5 Mg ha^{-1} (Table 3). The EONR for late-split application of N was 143 kg N ha^{-1} producing an estimated yield of 14.6 Mg ha^{-1} (Table 4). A greater RTN at the EONR was observed when N was late-split at \$733 ha^{-1} versus \$690 ha^{-1} when all N was applied early (Table 3).

Precipitation in Monmouth during the 2017 growing season was below average except in the month of July (Table 2), however, growing conditions were otherwise favorable and resulted in satisfactory corn grain yields. Yield averages in the C-S trial ranged from 12.5 Mg ha^{-1} in plots receiving no N fertilizer to 16.1 Mg ha^{-1} in plots receiving 280 kg N ha^{-1} with application timing proving to have little or no effect on yield at this rate. Response to N was nearly identical between application timings at all rates (Figure 5). A significantly higher yield of 15.7 Mg ha^{-1} was observed when all N was applied early with late-split application at this rate resulting in an average yield of 15.2 Mg ha^{-1} (Figure 5). The EONR for early N application was 146 kg N ha^{-1} compared to 168 kg N ha^{-1} when N was late-split with both application timings having an identical estimated yield of 15.9 Mg ha^{-1} at their respective rates (Table 3). A greater RTN of \$407 ha^{-1} was observed at the EONR when all N was applied early compared to \$384 ha^{-1} when N was late-split (Table 3). Yield averages in the C-C trial ranged from 11.3 Mg ha^{-1} in plots receiving no N fertilizer to 14.9 Mg ha^{-1} when 280 kg N ha^{-1} was applied early (Figure 6). Response to N was very similar between application timings at rates ≤168 kg N ha^{-1} at which point a marginally greater response to all N being applied early was observed (Figure 6). A significantly greater yield of 14.4 Mg ha^{-1} was observed when 112 kg N ha^{-1} was applied early compared to the late-split application at this rate which resulted in a yield of 13.2 Mg ha^{-1} (Figure 6). The EONR was found to be 181 kg N ha^{-1} when applied early, with an estimated yield of 14.5 Mg ha^{-1} at this rate (Table 3). The EONR for late-split application of N was observed to be at 165 kg N ha^{-1}, producing an estimated yield of 14.0 Mg ha^{-1}. A greater RTN of $332 ha^{-1} resulted from the early application of all N at the EONR compared to a RTN of $273 ha^{-1} when N was late-split (Table 3).

Regular rainfall occurred throughout the entire 2016 growing season in Urbana and was well above the 30-year state average (Table 2). Yield averages in the C-S trial ranged from 10.6 Mg ha^{-1} in plots receiving no N fertilizer to 15.1 Mg ha^{-1} in plots receiving 280 kg N ha^{-1} late-split. Response to N was very similar between application timings at all rates. Late-split application of N resulted in a significantly greater yield of 13.1 Mg ha^{-1} in comparison to 12.5 Mg ha^{-1} when all N was applied early at the 56 kg N ha^{-1} rate (Figure 7). Late-split application of 280 kg N ha^{-1} also resulted in a significantly greater yield of 15.1 Mg ha^{-1} versus early application of all N at this rate producing 14.5 Mg ha^{-1} (Figure 7). The EONR for early application was 147 kg N ha^{-1} producing an estimated yield of 14.6 Mg ha^{-1} (Table 3). The EONR when N was late-split was 137 kg N ha^{-1} with an estimated yield of 14.7 Mg ha^{-1} (Table 3). A greater RTN was observed when N was late-split at $527 ha^{-1} compared to $505 ha^{-1} when all N was applied early (Table 3). Yield averages in the C-C trials ranged from 6.5 Mg ha^{-1} in plots receiving no N fertilizer to 14.9 Mg ha^{-1} when 280 kg N ha^{-1} was applied early (Figure 8). Response to N was again very similar between application timings (Figure 8). Late-split application of 56 kg N ha^{-1} at VT resulted in a significantly greater yield of 10.8 Mg ha^{-1} compared to 9.9 Mg ha^{-1} when 56 kg N ha^{-1} was applied early (Figure 8). Early application of 112 kg N ha^{-1} resulted in a significantly greater yield of 12.7 Mg ha^{-1} compared a yield of 13.5 Mg ha^{-1} when N was late-split (Figure 8). The EONR when all N was applied early was found to be 184 kg N ha^{-1} versus 196 kg N ha^{-1} when N was late-split with both application timings producing an identical estimated yield of 14.7 Mg ha^{-1} at their respective rates (Table 3). A greater RTN of $1,129 ha^{-1} was found when all N was applied early compared to $1,120 ha^{-1} when N was late-split (Table 3). It should be noted that the RTN values from this trial are comparatively much higher than those observed in most other trials largely due to the low yields produced in plots receiving no N fertilizer.

Precipitation in Urbana during the month of May in 2017 was slightly greater than the 30-year state average but was noticeably lower during subsequent months of the growing season (Table 2). Yield averages in the C-S trial ranged from 9.2 Mg ha^{-1} in plots receiving no N fertilizer to 14.0 Mg ha^{-1} when 280 kg N ha^{-1} was late-split (Figure 9). Response to N was nearly identical between application timings across rates and no significant yield differences were observed between practices at any rate (Figure 9). The EONR for early application of N was 175 kg N ha^{-1} with an estimated yield of 13.4 Mg ha^{-1} (Table 3). The EONR for late-split application of N was 165 kg N ha^{-1} with an estimated yield of 13.2 Mg ha^{-1} (Table 3). Early application of all N resulted in a greater RTN at $506 ha^{-1} compared to $485 ha^{-1} when N application was late-split (Table 4). Yield averages in the C-C trial ranged from 11.0 Mg ha^{-1} in plots receiving no N fertilizer to 13.4 Mg ha^{-1} when 280 kg N ha^{-1} was applied early (Figure 10). Response to N was again found to be nearly identical between application timings at all rates and no significant yield differences were observed between treatments (Figure 10). Both application timings had an EONR of 153 Mg ha^{-1} with the application of all N early having an estimated yield of 13.1 Mg ha^{-1} versus 13.0 Mg ha^{-1} when N was late-split (Table 3). This difference, although small, resulted in a greater RTN of $191 ha^{-1} when all N was applied early at the EONR compared to $180 ha^{-1} when N was late-split (Table 3).

The C-S trial added in Neoga during 2017 received a large amount precipitation during the month of May and less than average rainfall for the remainder of the growing season with the exception of the month of July which produced a rainfall total just below the 30-year state average (Table 2). Yield averages in the trial ranged from 5.6 Mg ha^{-1} in plots receiving no N fertilizer to 9.8 Mg ha^{-1} in plots receiving 224 kg N ha^{-1} late-split (Figure 11). Response to N was very similar between application timings at all rates and no significant yield differences were observed within the trial (Figure 11). The EONR for early application of all N was 162 kg N ha^{-1} with an estimated yield of 9.2 Mg ha^{-1} (Table 3). The EONR for the late-split application of N was 170 kg N ha^{-1} with an estimated yield of 9.3 Mg ha^{-1} (Table 3). A greater RTN at the EONR was observed when N was late-split at \$432 ha^{-1} compared to \$418 ha^{-1} when all N was applied early (Table 3).

Rainfall monthly totals were below the 30-year state average in Perry during the 2016 growing season with the exception of the month of July (Table 2). Yield averages in the C-S trial ranged from 9.7 Mg ha^{-1} in plots receiving no N fertilizer to 15.0 Mg ha^{-1} which was produced in plots receiving late-split N at both the 168 and 224 kg N ha^{-1} rates (Figure 12). Response to N was marginally greater when all N was applied early at low rates and very similar at rates ≥168 kg N ha^{-1} (Figure 12). The EONR when all N was applied early was 125 kg N ha^{-1} with an estimated yield of 14.8 Mg ha^{-1} (Table 3). The EONR when N was late-split was155 kg N ha^{-1} with an estimated yield of 14.9 Mg ha^{-1} (Table 3). RTN values between application timings were very similar with early application resulting in a RTN of \$687 ha^{-1} and late-split application resulting in a RTN of \$686 ha^{-1}. Yield averages in the C-C trial ranged from 6.3 Mg ha^{-1} in plots receiving no N fertilizer to 14.6 Mg ha^{-1} when 280 kg N ha^{-1} was applied early (Figure 13). Response to N was very similar between application timings and no significant yield differences were observed within the trial (Figure 13). The EONR for early application of N was 155 kg N ha^{-1} while the EONR for late-split application of N was 171 kg N ha^{-1} with both treatments having an estimated yield of 14.3 Mg ha^{-1} at their respective EONR (Table 3). A greater RTN of $1,115 ha^{-1} was observed when all N was applied early compared a RTN of $1,096 ha^{-1} when N application was late-split (Table 3). Again, it should be noted that the RTN values observed in the trial were inflated largely due to the low yields produced by plots receiving no N fertilizer.

Precipitation in Perry during the month of May in 2017 was greater than the 30-year state average with rainfall being consistent, although lower than average, during subsequent months (Table 2). Yield averages in the C-S trial ranged from 10.3 Mg ha^{-1} in plots receiving no N fertilizer to 14.1 Mg ha^{-1} when 24 kg N ha^{-1} was applied early (Figure 14). Response to N was found to be very similar between applications at all rates with no significant yield differences occurring within the trial (Figure 14). The EONR when all N was applied early was 135 kg N ha^{-1} while the EONR for late-split application of N was 154 kg N ha^{-1} with both application timings having an estimated yield of 13.7 Mg ha^{-1} at their respective EONR (Table 3). A greater RTN of $417 ha^{-1} was found when all N was applied early compared to $387 ha^{-1} when N was late-split (Table 3). Yield averages in the C-C trial ranged from 6.1 Mg ha^{-1} in plots receiving no N fertilizer to 13.5 Mg ha^{-1} in plots receiving 224 kg N ha^{-1} late-split (Figure 15). Response to N was greater when all N was applied early at low rates and very similar at rates ≥168 kg N ha^{-1} (Figure 15). The EONR when all N was applied early was 143 kg N ha^{-1} with an estimated yield of 12.9 Mg ha^{-1} (Table 3). The EONR when N was late-split was 176 kg N ha^{-1} with an estimated yield of 13.0 Mg ha^{-1} (Table 3). A greater RTN resulted when all N was applied early at $933 ha^{-1} compared to $922 ha^{-1} when N was late-split (Table 3).

<u>Grain Protein</u>

Grain protein concentrations were measured in 2016 and 2017 in both the corn following corn and corn following soybean trials conducted in Urbana. Research studying the application of N fertilizers during late vegetative growth stages in cereal crops has found that such late application timing often increases grain protein concentrations. Grain protein concentrations were found to be very similar between application timings at high N rates (Figures 16-19). However, it was observed that late-split N application increased grain protein concentrations at low application rates with significant differences observed in two of the four trials at the 56 kg N ha^{-1} rate. Yet results at higher N Rates were not always consistent. When all N was applied at planting, significantly greater grain protein concentrations were observed at the 112 kg N ha^{-1} rate in the 2017 corn following corn trial and the 224 kg N ha^{-1} rate in the 2017 corn following soy trial. These results also corresponded to a numerical increase in grain yields with early N application at 112 and 224 kg N ha^{-1} in 2017. Although not significantly greater, these grain yield increases may indicate that plant health was improved by the presence of plant available N throughout vegetative growth resulting in a greater capacity for grain protein assimilation during grain fill.

Grain N Content

Grain N content was also calculated using the NIR measurements taken from the Urbana trials conducted in 2016 and 2017 (Figures 20-23). Total grain N contents were found to be consistently higher at the 56 kg N ha^{-1} rate when N was late-split. Total grain N contents were otherwise found to be very similar between application treatments at rates $\geq$ 112 kg N ha^{-1} where grain yields were not significantly different.

SPAD Chlorophyll Meter Readings

Ear leaf chlorophyll concentrations were measured using a SPAD meter in 2016 and 2017 in both the corn following corn and corn following soybean trials conducted in Urbana prior to nitrogen application at VT and following application. These measurements were taken to find if plants receiving a portion of N fertilizer late in vegetative growth were capable of producing chlorophyll at levels comparable to plants that received all N at planting after application and if so, did an increase in chlorophyll concentration during reproductive growth stages enable the plant to produce comparable or increased grain yields (Figures 24-27). Chlorophyll concentrations were found to be lower prior to application in plots receiving late-split N at the 56 kg N ha^{-1} and 112 kg N ha^{-1} rates, and similar between treatments at rates $\geq$168 kg N ha^{-1}. Readings taken after application at VT indicated plants receiving late-split N were capable of producing increased amounts of chlorophyll through reproductive growth stages and concentrations were found to be similar or just below concentrations observed in plots receiving all N at planting in most instances.

When chlorophyll concentration readings taken in plots receiving late-split N are plotted versus grain yield values it can be seen that plants with relatively low chlorophyll concentrations were still capable of comparable grain yields to those in plots receiving all N early(Figures 28-29). When readings taken after application in plots receiving late-split N are plotted versus grain yield we see that the increase in chlorophyll concentration is more representative of these grain yield levels. This difference in representation indicates that SPAD meter readings taken later in the season or after nutrient application may be a greater indicator than readings taken earlier in the season.

Summary and Conclusions

Over two years, fifteen site-locations, and a range of growing conditions we found that N responses, including EONR values and estimated yields at the EONR, differed little between the application of all N early compared to the late-split application of N at VT. Observed corn grain yields were very similar between application timings at each location regardless of weather patterns and while significant yield differences did occur in some instances, there is no indication that either practice holds an advantage over the other in terms of corn grain production. Grain protein, nitrogen, and chlorophyll contents were also found to be very similar in the four trials conducted in Urbana during the 2016 and 2017 growing seasons, with no consistent improvement in any category between N application timings.

Although research indicates that splitting and/or delaying application of N fertilizers may increase NUE as well as N fertilizer recovery efficiency, two key components within the idea of "N synchronization", the use of this management practice must first prove to be both agronomically and economically superior to management practices currently being used for widespread adoption to occur. RTN values between application timings were found to be very similar at each location and any increases in corn grain yield or return to nitrogen values achieved through the use of a late-split application must be addressed with consideration to the additional costs and risks associated with the practice. The investment in high-clearance machinery required for application, the cost for fuel, time and labor, the possibility that weather conditions may not allow for application in a timely manner or prevent late-applied N from reaching plant roots, and the impacts that an additional trip across the field may have such as unnecessary soil compaction all work against the widespread adoption of this practice.

Based on the results obtained through this research, late-split application of N on medium- to heavy-textured soils cannot be considered an agronomically or economically advantageous practice in comparison to the application of all N fertilizer at or near planting and is not recommended as a best management practice. Despite results from this study indicating lack of response to late-split N, it did produce yields equal to those from early-applied N, so the late-applied N was available to the plants. We did not have in this study any location in which conditions (wet soils during vegetative development) were conducive to high N loss, so we were unable to test the possibility that late-split N could help alleviate yield loss under such conditions. Our finding that plant chlorophyll, grain protein, and grain N concentrations respond to late-applied N indicate plants are capable of utilizing plant available N supplied through fertilizer applications as late as VT, suggesting some possible utility of the practice in high N-loss conditions.

Tables and Figures

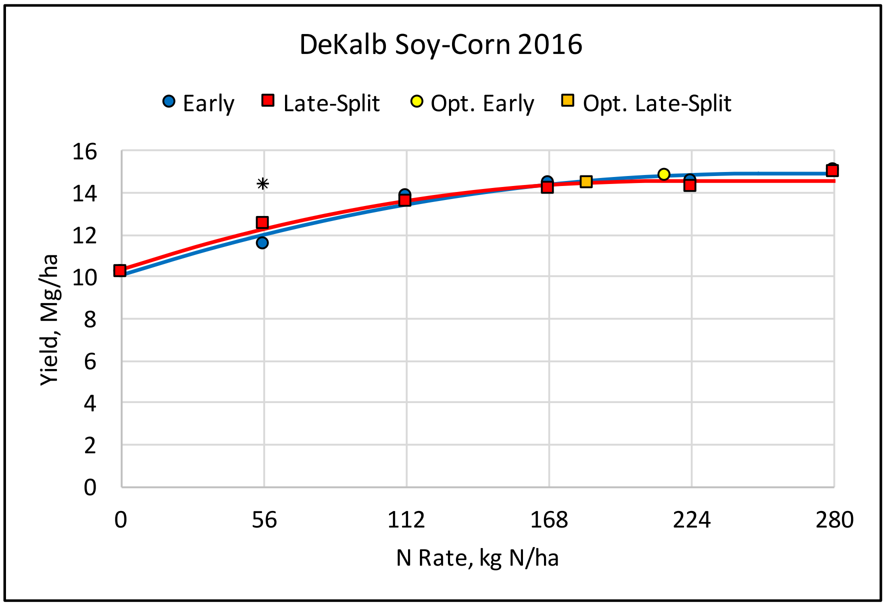
Table 1. Location, soil type and organic matter at 2016 and 2017 sites

Site	Lat., Long.	Primary Soil Type	SOM (%)
		2016	
DeKalb S-C	41.8444, -88.8562	Elpaso silty clay loam	5.2
Monmouth S-C	40.9338, -90.7267	Muscatune silt loam	3.1
Monmouth C-C	40.9331, -90.7257	Muscatune silt loam	3.2
Urbana S-C	40.0252, -88.1348	Flanagan silt loam	3.9
Urbana C-C	40.0328, -88.1344	Catlin silt loam	3.3
Perry S-C	39.8038, -90.8216	Timewell silt loam	2.7
Perry C-C	39.7968, -90.8198	Winfield silty clay loam	2.4
		2017	
DeKalb S-C	41.8445, -88.8491	Flanagan silt loam	4.0
Monmouth S-C	40.9228, -90.7266	Muscatune silt loam	4.6
Monmouth C-C	40.9260, -90.7255	Muscatune silt loam	5.5
Urbana S-C	40.0246, -88.1348	Flanagan silt loam	3.7
Urbana C-C	40.0243, -88.1349	Flanagan silt loam	3.9
Neoga S-C	39.2540, -88.4191	Bluford-Darmstadt silt loam	2.3
Perry S-C	39.8038, -90.8225	Timewell silt loam	2.6
Perry C-C	39.8038, -90.8216	Timewell silt loam	2.7

Table 2. Recorded rainfall for 2016 and 2017 trial locations and 30-year average rainfall by month

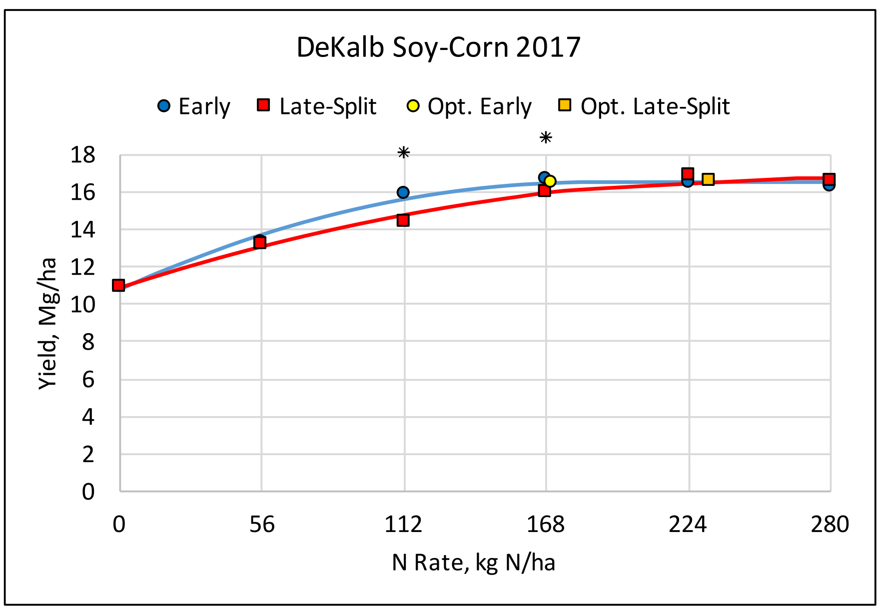
	May	June	July	August	September
			mm		
			30-year average		
DeKalb	116	105	111	111	83
Monmouth	121	114	104	120	95
Urbana	124	110	119	100	80
Perry	107	109	110	98	92
			2016		
DeKalb	205	94	153	135	48
Monmouth	97	120	183	129	45
Urbana	119	145	112	105	140
Perry	89	18	185	86	45
			2017		
DeKalb	102	69	173	47	2
Monmouth	74	62	130	43	16
Urbana	143	65	57	56	21
Perry	164	93	82	87	14
Neoga	147	54	50	15	3

Figure 1. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following soybean at the DeKalb site in 2016.



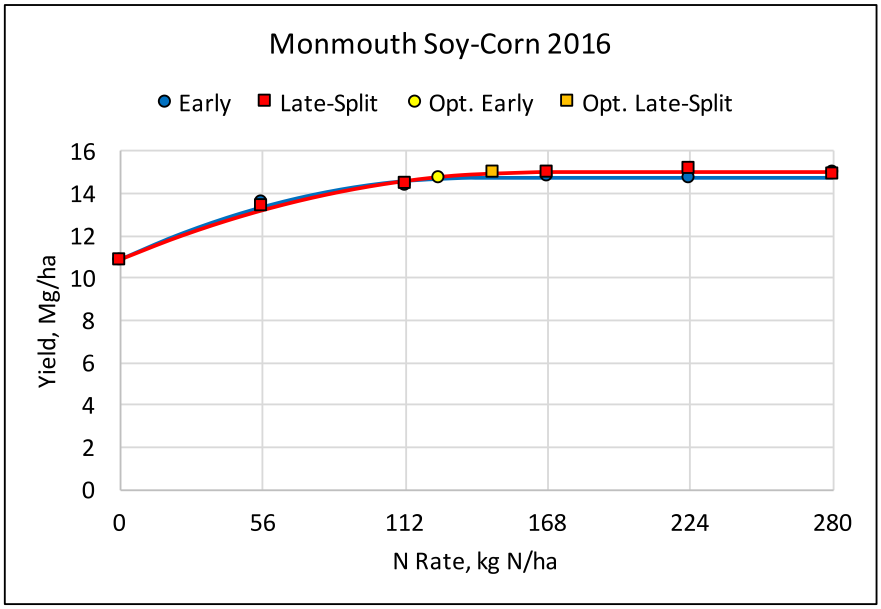
Opt. = calculated optimum
* Denotes a significant yield differences between application timings at that N rate

Figure 2. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following soybean at the DeKalb site in 2017.



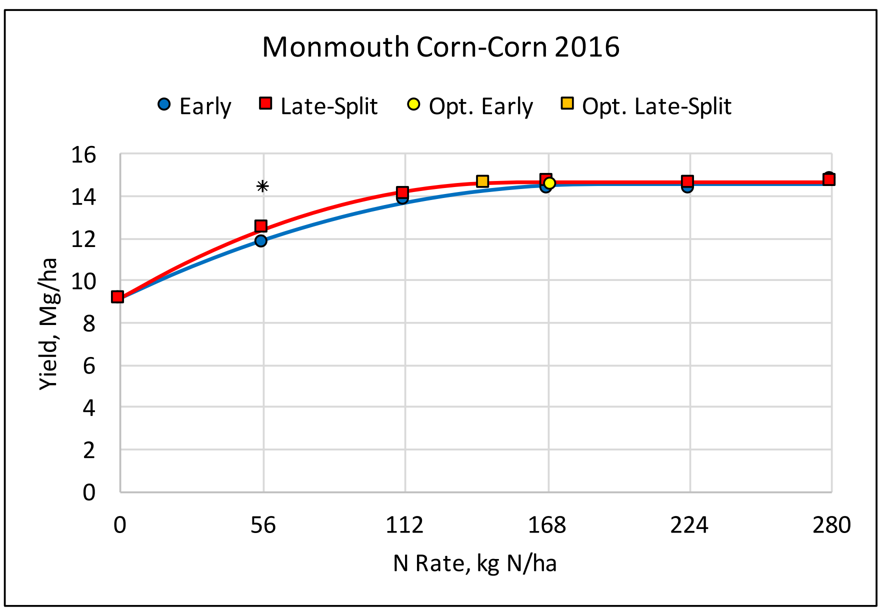
Opt. = calculated optimum
* Denotes a significant yield differences between application timings at that N rate

Figure 3. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following soybean at the Monmouth site in 2016.



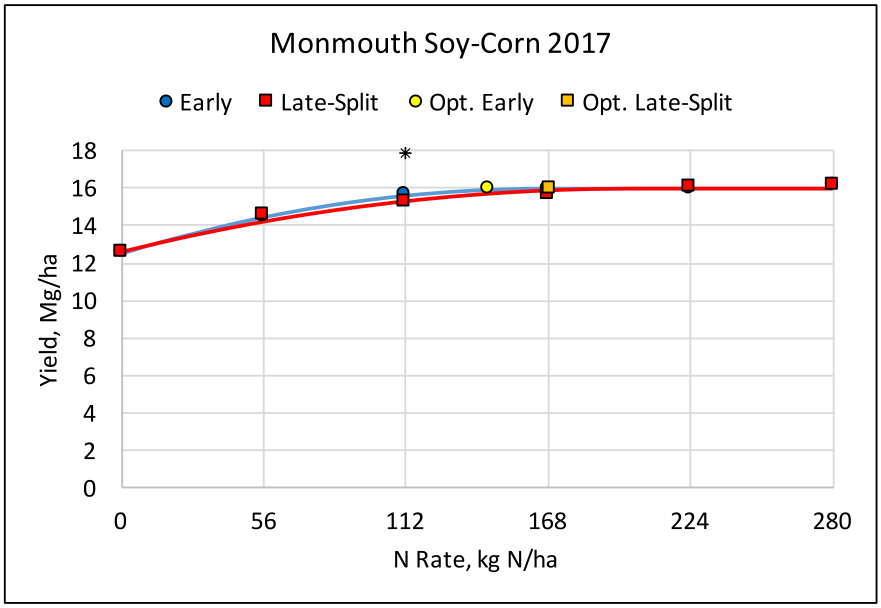
Opt. = calculated optimum

Figure 4. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following corn at the Monmouth site in 2016.



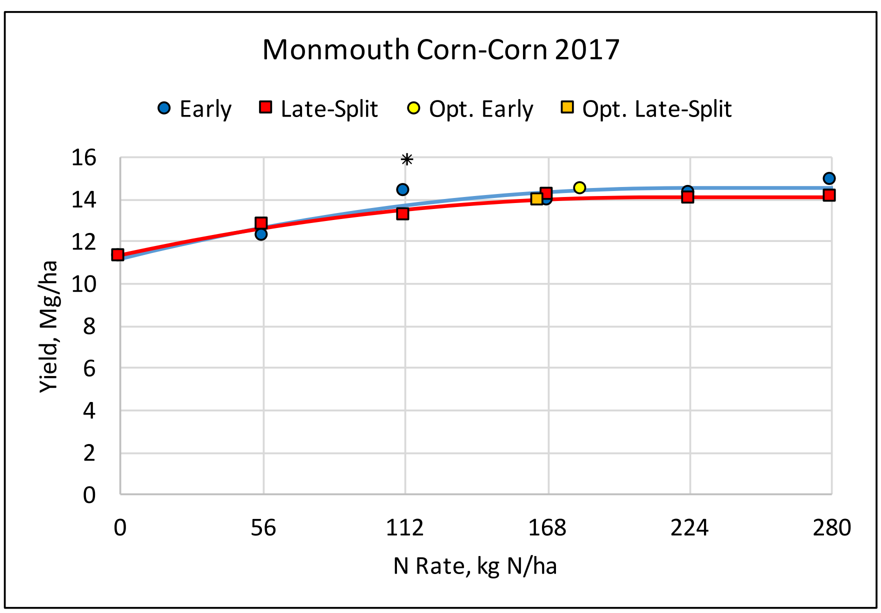
Opt. = calculated optimum
* Denotes a significant yield differences between application timings at that N rate

Figure 5. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following soybean at the Monmouth site in 2017.



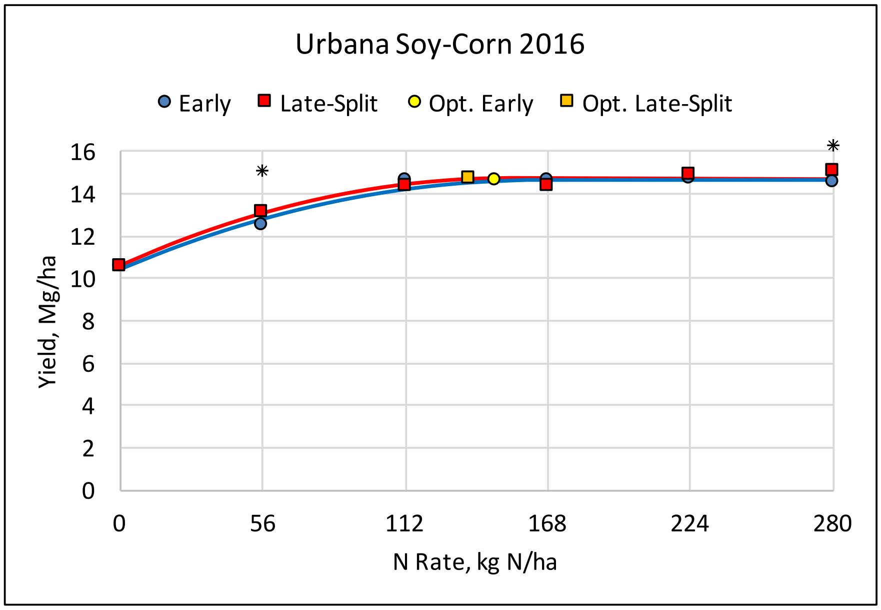
Opt. = calculated optimum
* denotes a significant yield differences between application timings at that N rate

Figure 6. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following corn at the Monmouth site in 2017.



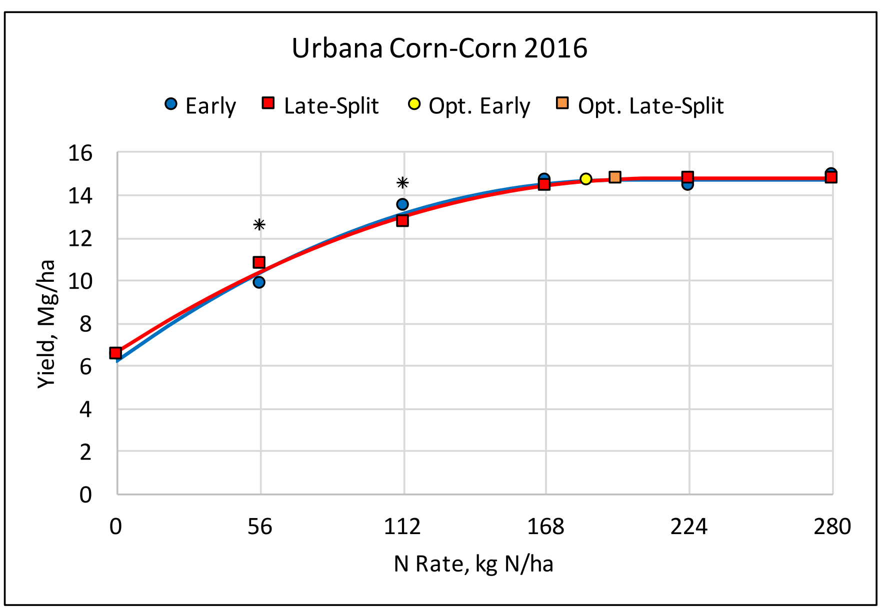
Opt. = calculated optimum
* Denotes a significant yield differences between application timings at that N rate

Figure 7. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following soybean at the Urbana site in 2016.



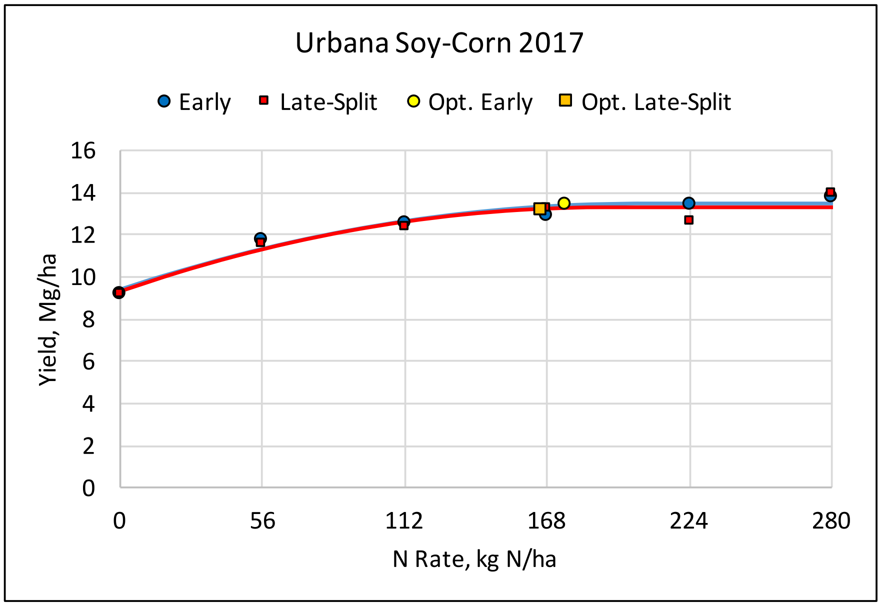
Opt. = calculated optimum
* Denotes a significant yield differences between application timings at that N rate

Figure 8. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following corn at the Urbana site in 2016.



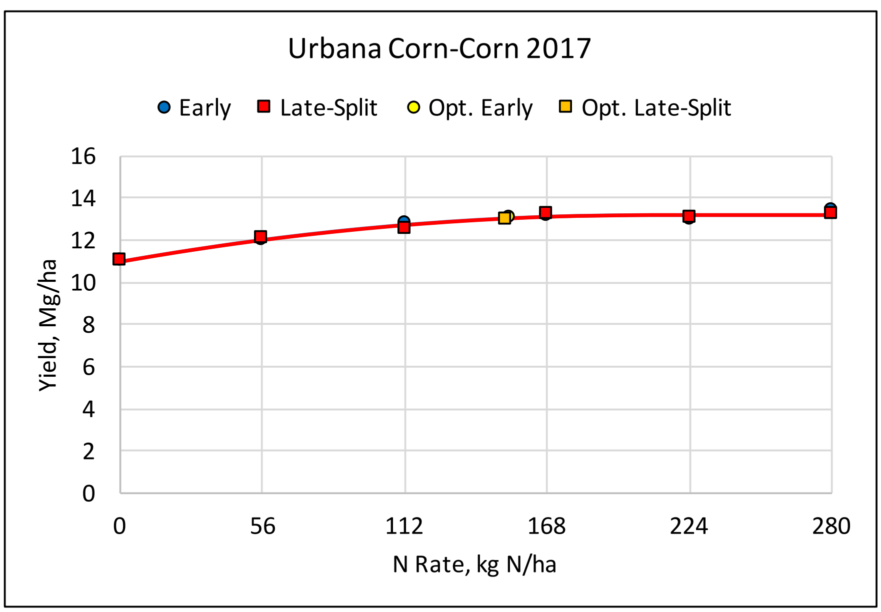
Opt. = calculated optimum
* Denotes a significant yield differences between application timings at that N rate

Figure 9. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following soybean at the Urbana site in 2017.



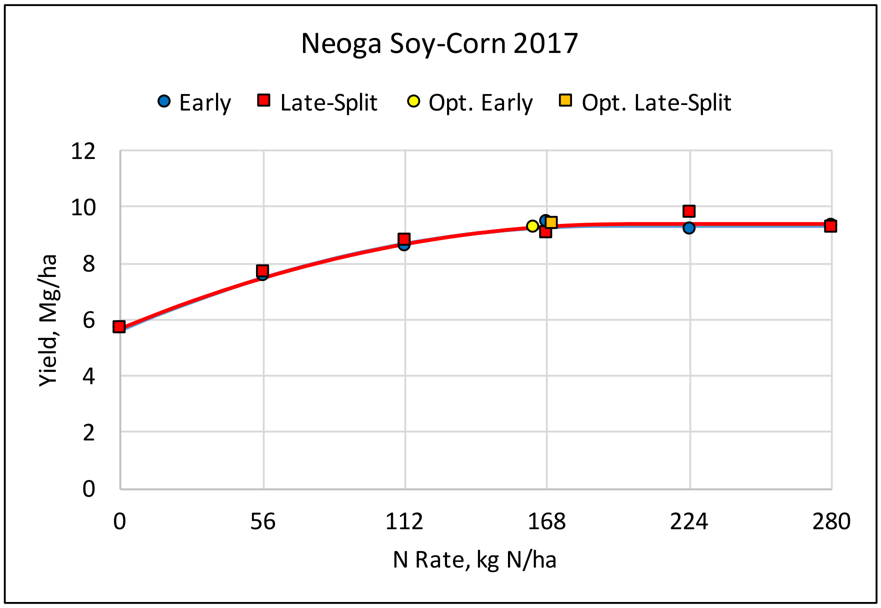
Opt. = calculated optimum

Figure 10. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following corn at the Urbana site in 2017.



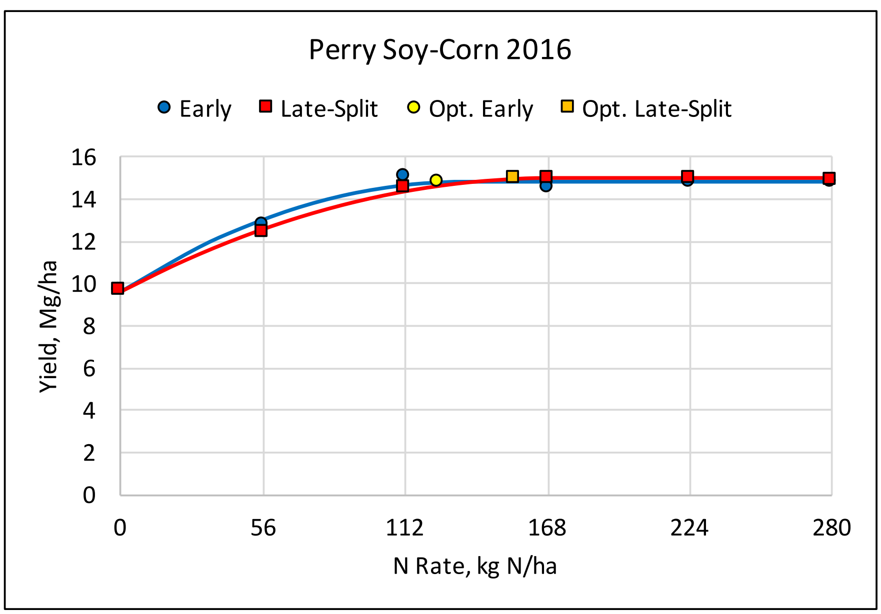
Opt. = calculated optimum

Figure 11. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following soybean at the Neoga site in 2017.



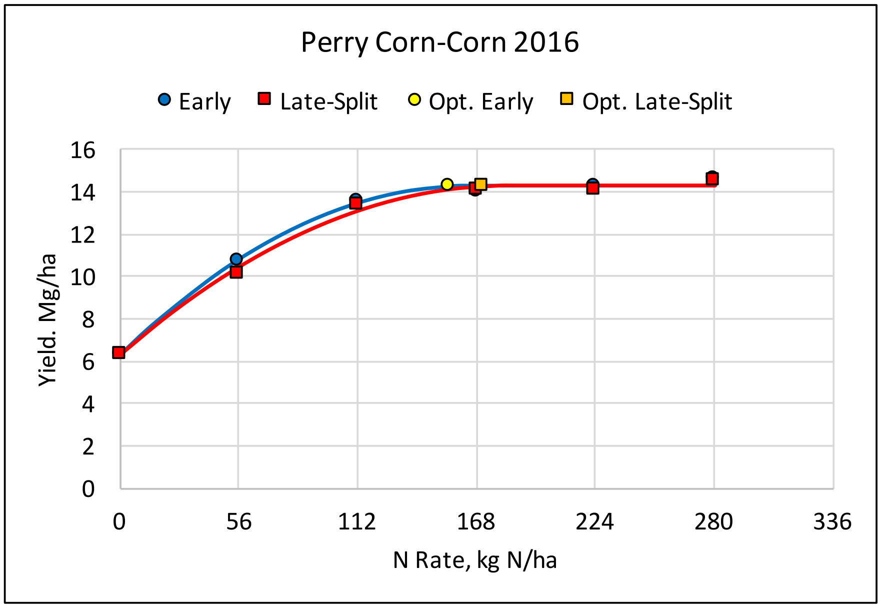
Opt. = calculated optimum

Figure 12. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following soybean at the Perry site in 2016.



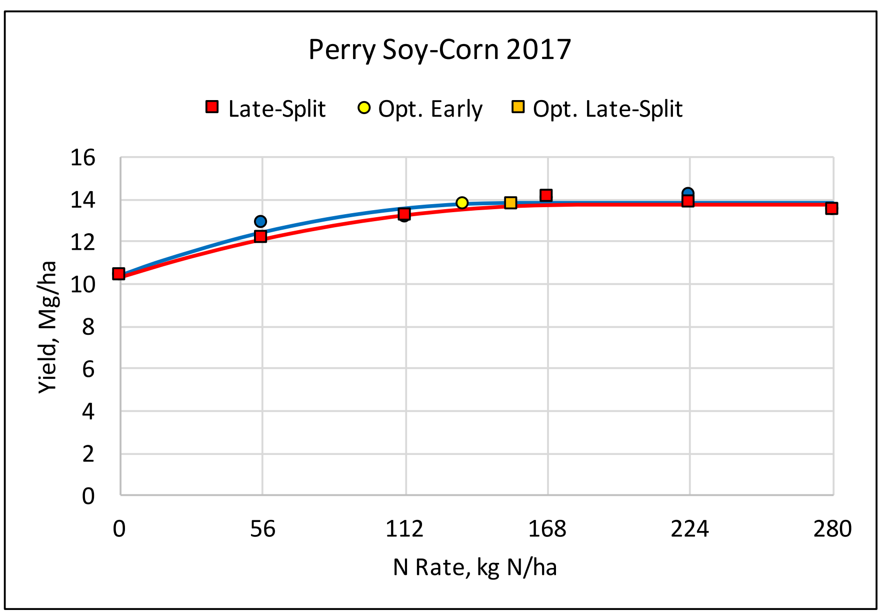
Opt. = calculated optimum

Figure 13. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following corn at the Perry site in 2016.



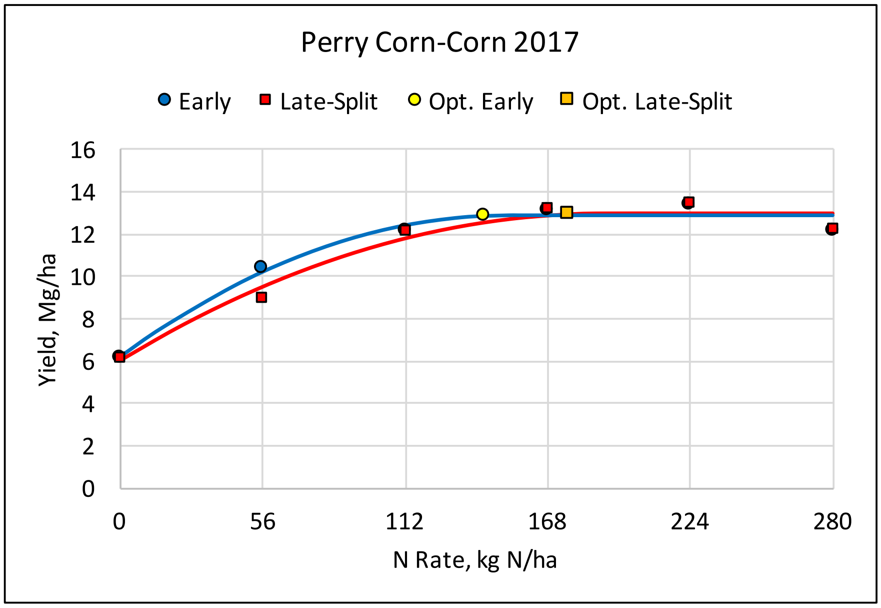
Opt. = calculated optimum

Figure 14. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following soybean at the Perry site in 2017.



Opt. = calculated optimum

Figure 15. Corn yield response to N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) applications to corn following corn at the Perry site in 2017.

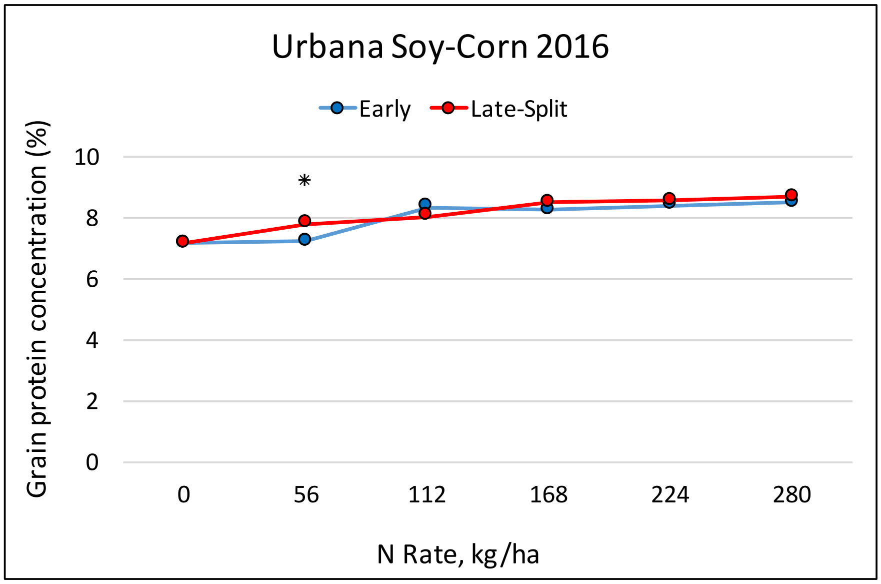


Opt. = calculated optimum

Table 3. Economically optimum N rate (EONR), yield at the EONR (EOY), and Return to N (RTN) of early and early + late-split N in 2016 and 2017 trials in Illinois

Crop sequence	Site	EONR		EOY		RTN	
	2016						
		Early	Late-Split	Early	Late-Split	Early	Late-Split
		----kg N ha^{-1} ----		------Mg ha^{-1} -----		-----$ ha^{-1} -----	
Soy-corn	DeKalb	214	183	14.8	14.5	$531	$511
	Monmouth	126	147	14.7	15.0	$499	$515
	Perry	125	155	14.8	14.9	$687	$686
	Urbana	144	139	14.6	14.7	$505	$527
	4-site average	152	156	14.7	14.8	$556	$560
Corn-corn	Monmouth	169	144	14.5	14.6	$690	$733
	Perry	156	170	14.3	14.3	$1,115	$1,096
	Urbana	186	196	14.7	14.7	$1,129	$1,120
	3-site average	170	170	14.5	14.5	$978	$983
	2017						
		EONR		EOY		RTN	
		Early	Late-Split	Early	Late-Split	Early	Late-Split
		----kg N ha^{-1} ----		------Mg ha^{-1}-----		---------$ ha^{-1} ---------	
Soy-corn	DeKalb	170	233	16.5	16.6	$730	$694
	Monmouth	146	168	15.9	15.9	$407	$384
	Neoga	162	170	9.2	9.3	$418	$432
	Perry	135	154	13.7	13.7	$417	$387
	Urbana	175	165	13.4	13.2	$506	$485
	5-site average	158	178	13.7	13.7	$496	$476
Corn-corn	Monmouth	181	165	14.5	14.0	$332	$273
	Perry	143	176	12.9	13.0	$933	$922
	Urbana	153	153	13.1	13.0	$191	$180
	3-site average	159	168	13.6	13.4	$488	$463

Figure 16. Grain protein concentration measurements observed when N was applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) to corn following soybean at the Urbana site in 2016.



* Denotes a significant difference in grain protein concentration between application timings at that N rate

Figure 17. Grain protein concentration measurements observed when N was applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) to corn following corn at the Urbana site in 2016.

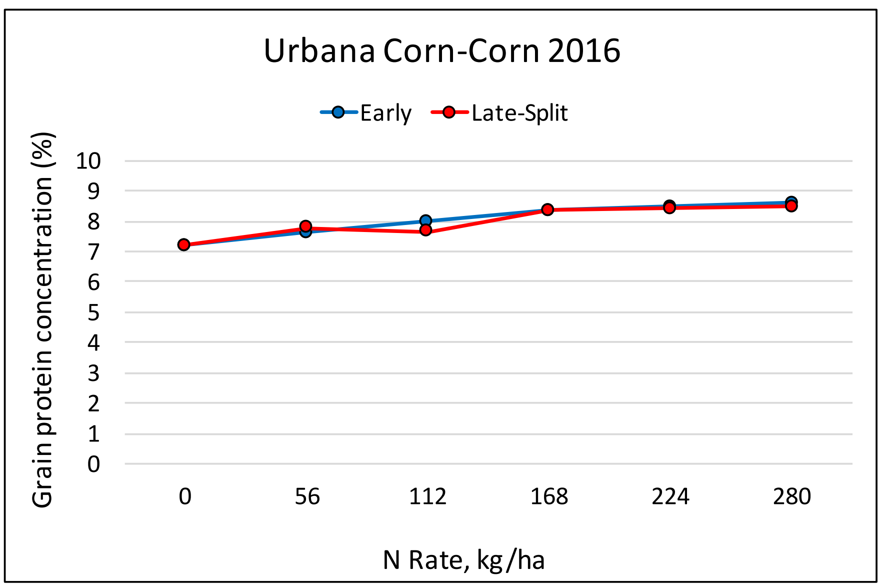
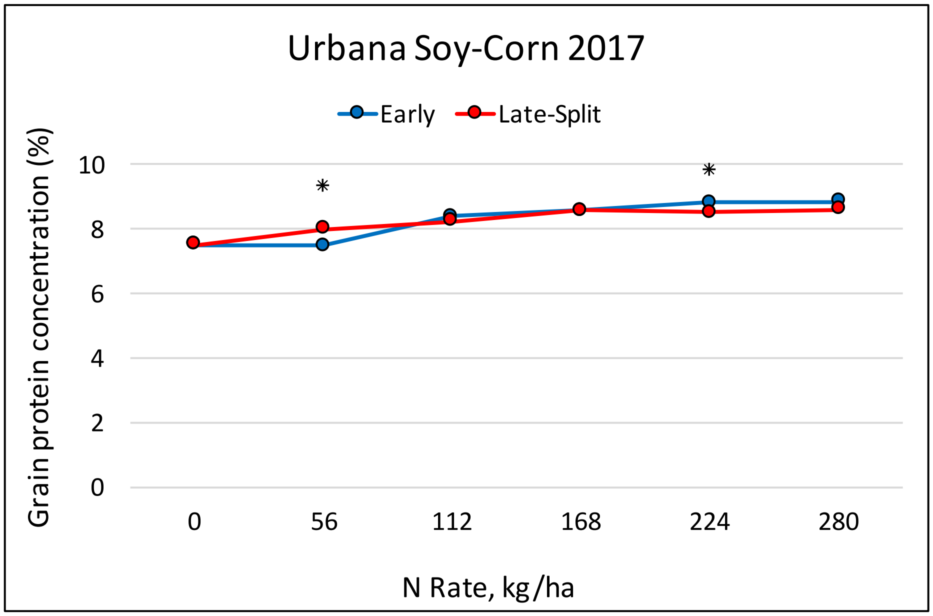
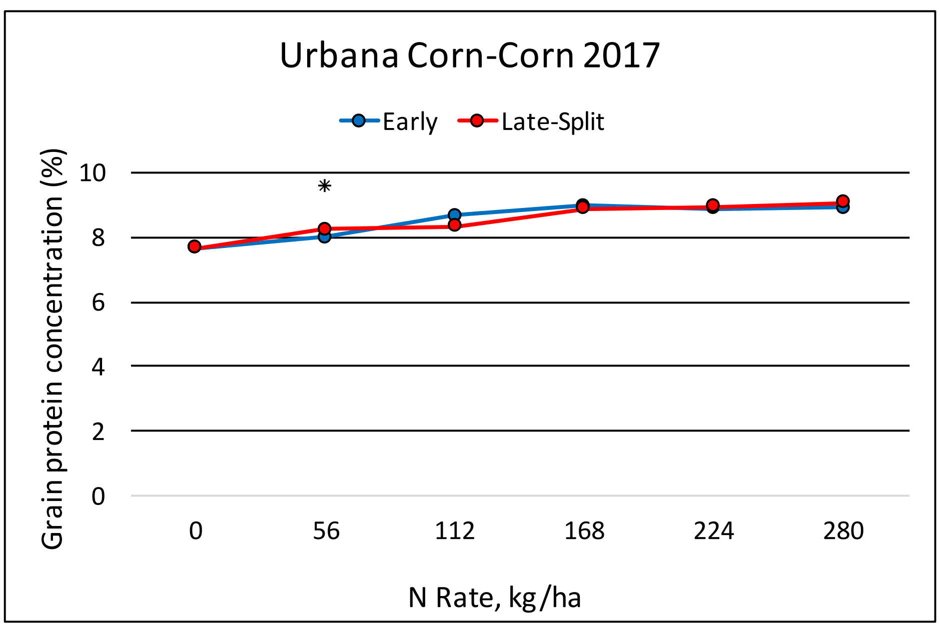


Figure 18. Grain protein concentration measurements observed when N was applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) to corn following soybean at the Urbana site in 2017.



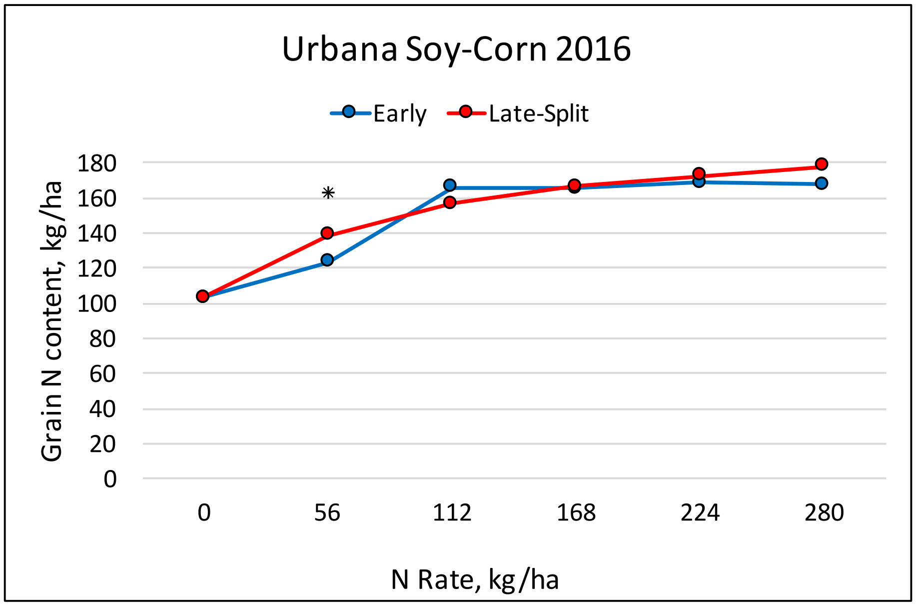
* Denotes a significant difference in grain protein concentration between application timings at that N rate

Figure 19. Grain protein concentration measurements observed when N was applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) to corn following corn at the Urbana site in 2017.



* Denotes a significant difference in grain protein concentration between application timings at that N rate

Figure 20. Response of grain N content to N rate with N applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) to corn following soybean at Urbana, 2016.



* Denotes a significant difference in grain N content between application timings at that N rate

Figure 21. Grain N concentration measurements observed when N was applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) to corn following corn at the Urbana site in 2016.

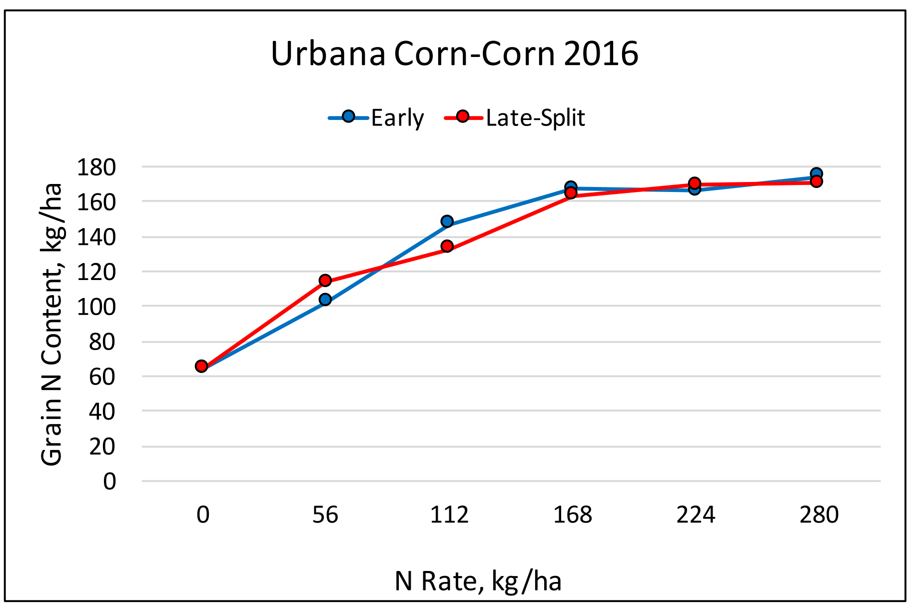
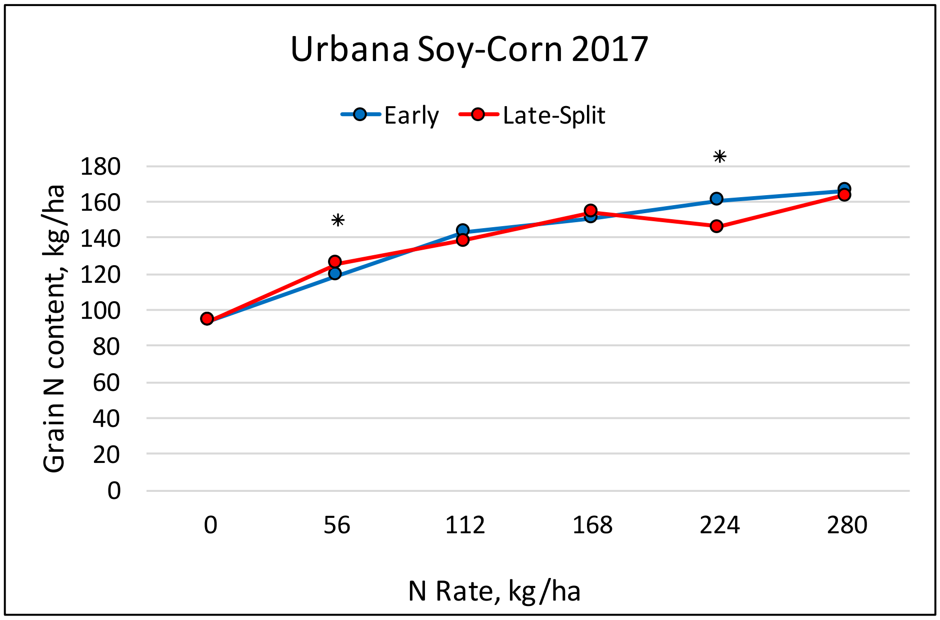
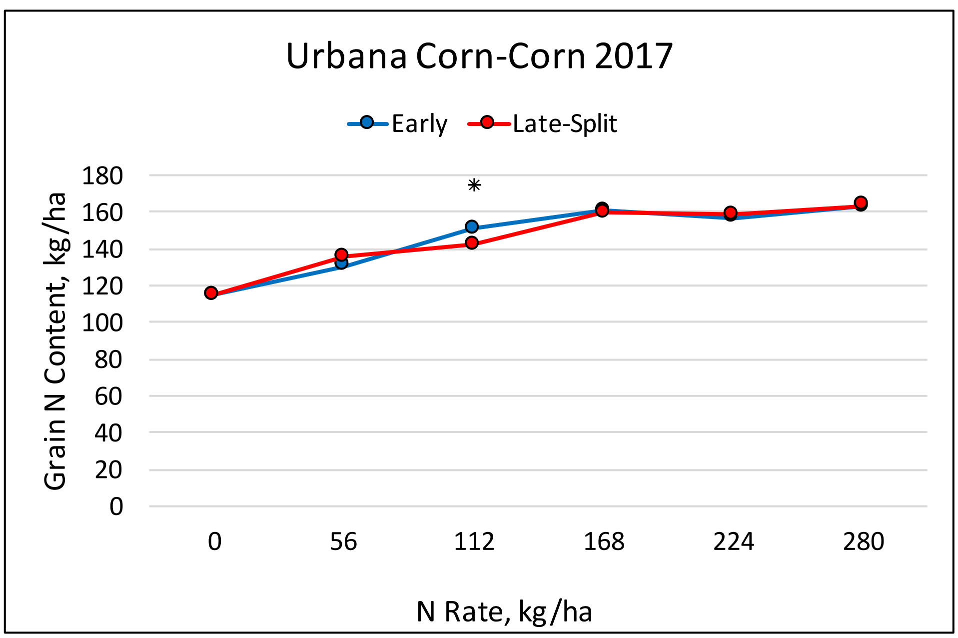


Figure 22. Grain N concentration measurements observed when N was applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) to corn following soybean at the Urbana site in 2017.



* Denotes a significant difference in grain N content between application timings at that N rate

Figure 23. Grain N concentration measurements observed when N was applied at planting (Early) and early + 56 kg N ha^{-1} at VT stage (Late-Split) to corn following corn at the Urbana site in 2017.



* Denotes a significant difference in grain N content between application timings at that N rate

Figure 24. Chlorophyll concentration (SPAD readings) taken using a SPAD meter before and after application of N at VT to corn following soybean at the Urbana site in 2016.

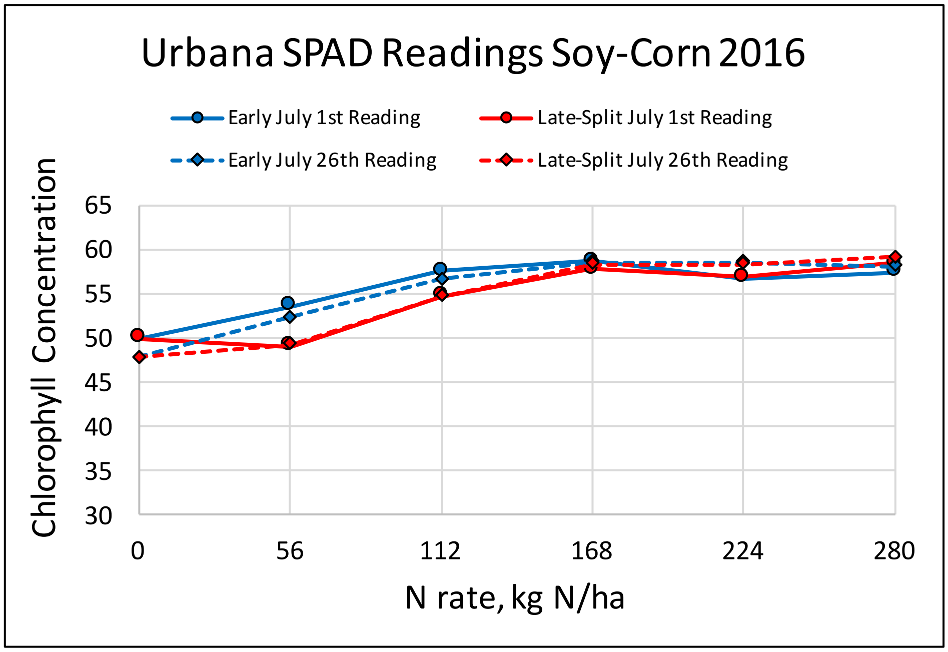


Figure 25. Chlorophyll concentration measurements taken using a SPAD meter before and after application of N at VT to corn following corn at the Urbana site in 2016.

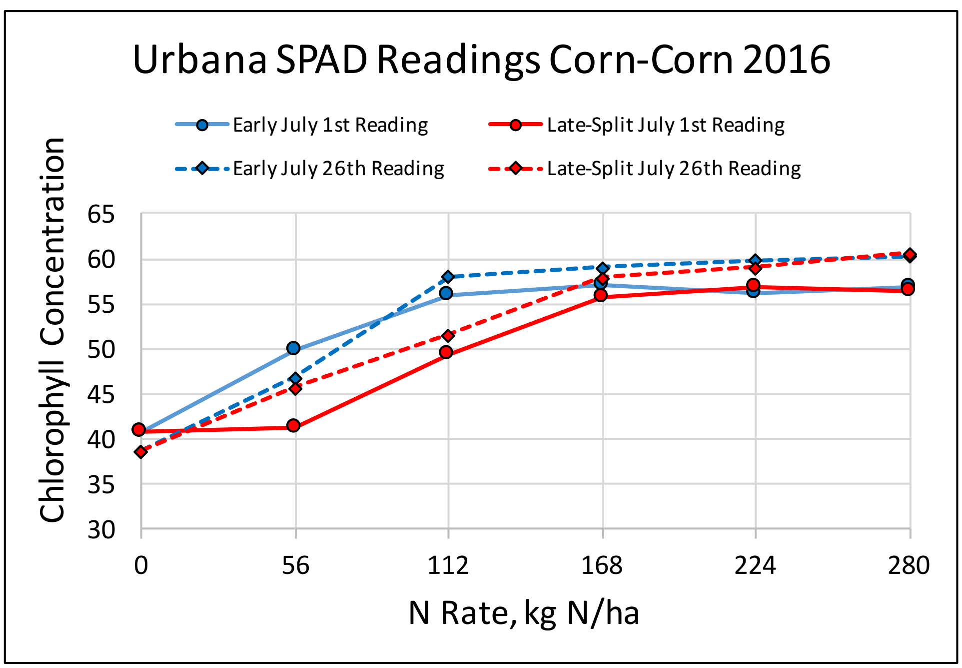


Figure 26. Chlorophyll concentration measurements taken using a SPAD meter before and after application of N at VT to corn following soybean at the Urbana site in 2017.

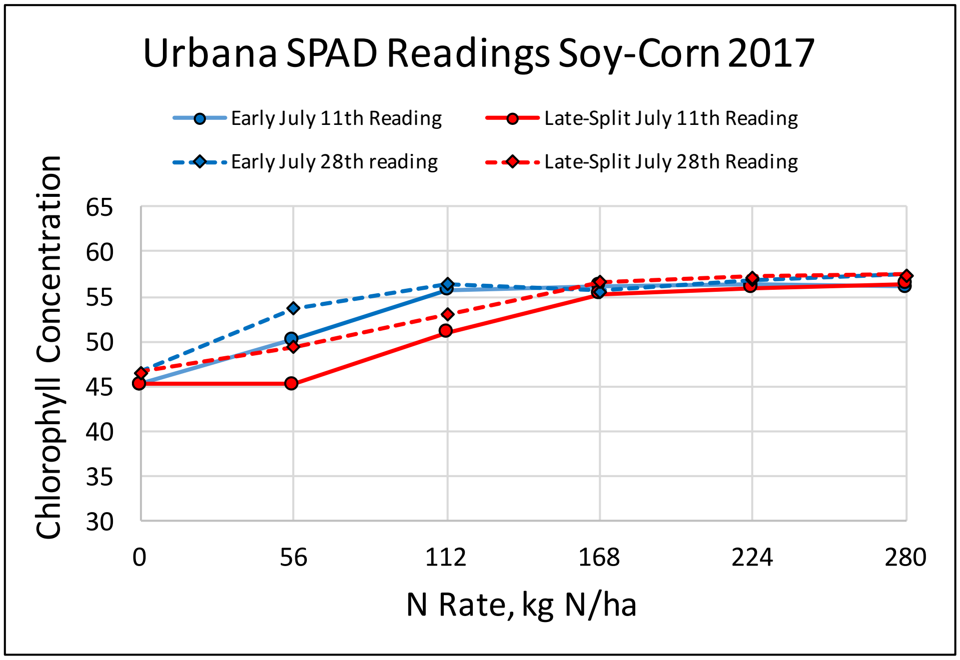


Figure 27. Chlorophyll concentration measurements taken using a SPAD meter before and after application of N at VT to corn following corn at the Urbana site in 2017.

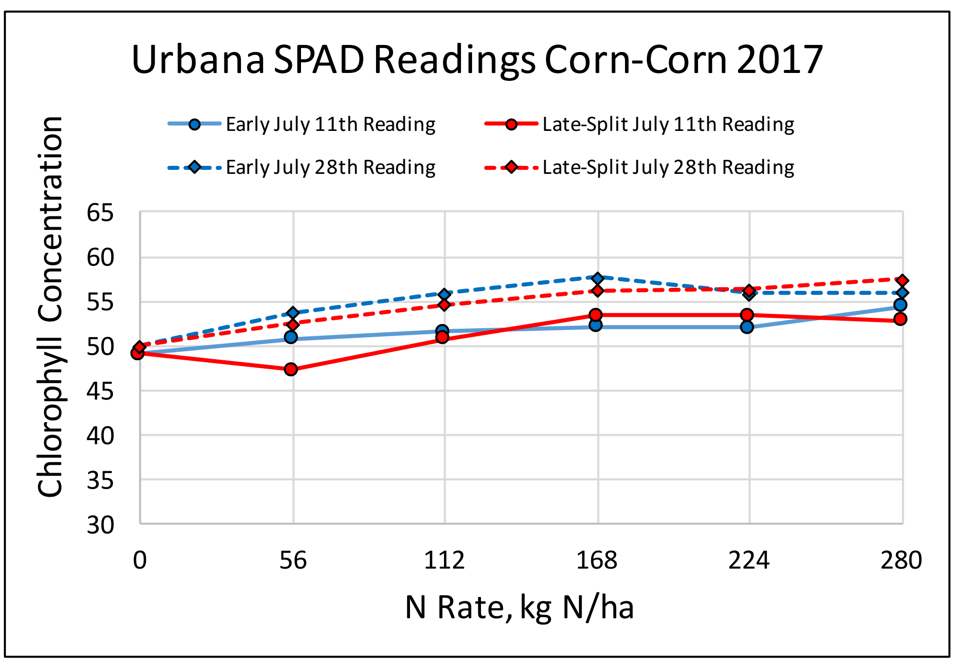


Figure 28. Chlorophyll concentration measurements taken using a SPAD meter after application of N at VT to corn following soybean plotted versus observed grain yield at the Urbana site in 2016 and 2017.

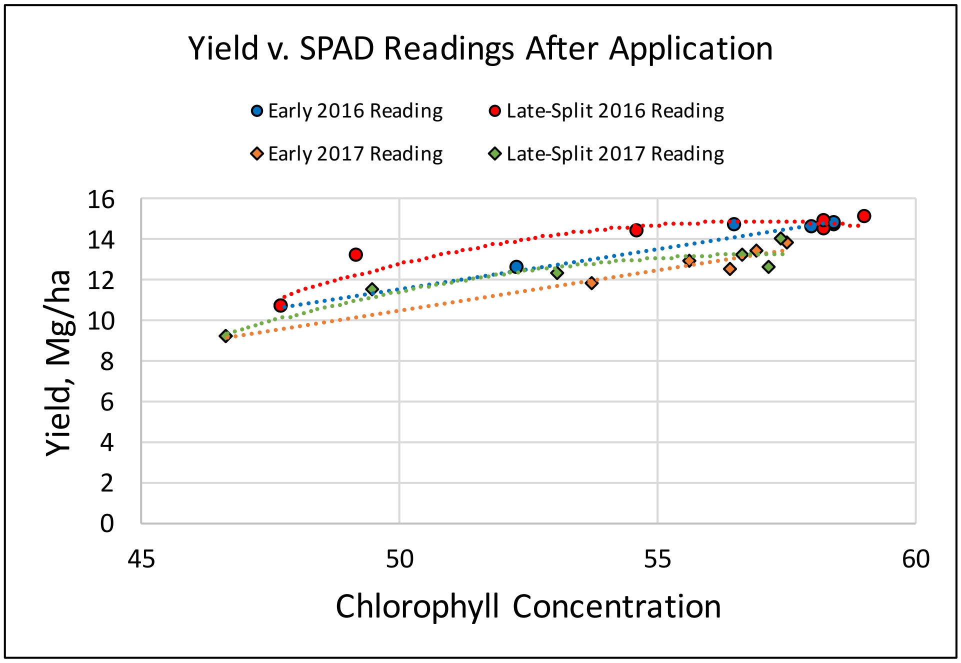
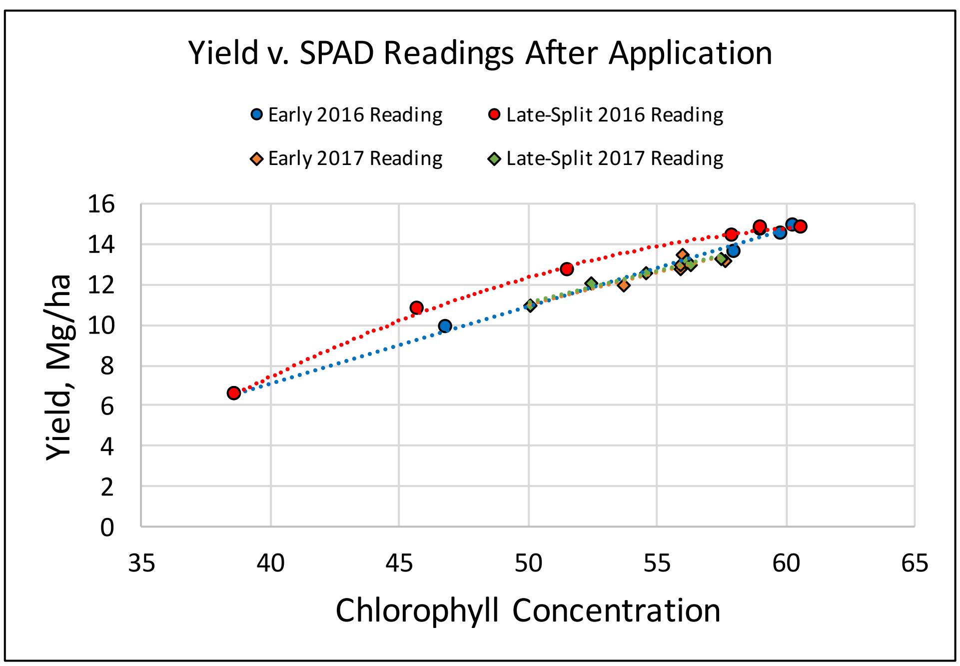


Figure 29. Chlorophyll concentration measurements taken using a SPAD meter after application of N at VT to corn following corn plotted versus observed grain yield at the Urbana site in 2016 and 2017.



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