CORN YIELD FOLLOWING A DELAYED APPLICATION OF NITROGEN

BY

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THESIS

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ABSTRACT

Delaying some of the N supplied to the corn crop is considered a way to increase N uptake and yield and to limit N losses, but the length of the delay may increase the risk of yield loss. We conducted a 3-year experiment at Urbana, Illinois in which half of the N (112 kg N ha\(^{-1}\)) was injected as UAN at planting and the other half or all (224 kg N ha\(^{-1}\)) of the N was dribbled UAN next to the row, at each of eight stages ranging from V3 to R3. In corn following soybean, when half of the N was applied at planting, the other half could be applied as late as R2 without significant yield loss, and application at R3 produced 92% of yield that the treatment with the second application at V3 did. Delaying application of all 224 kg N ha\(^{-1}\) through V15 did not decrease yield significantly, but yield declined by 12, 19 and 37% with application at VT, R2 and R3, respectively. In corn following corn, delaying the second half of the N to R3 produced 96% of the yield that the second application at V3 did, and none of the delayed timings lowered yields significantly. Delaying all the N to V9 did not significantly decrease yield, but yield thereafter decreased as the delay increased, from 11% less at V12 to 42% less at R3. Without N at planting, N needed to be applied by mid-vegetative stages to prevent yield loss, but when half the N was applied at planting, there was surprisingly little yield loss from delaying application until past pollination. SPAD readings showed that the split-N treatments were able to recover their healthy leaf color no matter how late N was applied, but with no N at planting, plants could not regain their full leaf color (or yield) if N was applied later than mid-vegetative stages. Our results indicate that even a lengthy delay in application of N can result in full yields, especially when half of the N is applied early. This application window is shortened if all of the N is delayed, in which case application should be made before plants reach mid-vegetative growth stages.
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Introduction

Nitrogen (N) is the supplied nutrient present in corn with the greatest quantities and has the highest concentration in dry matter of corn *Zea mays L* after the constituent elements C, H, and O. Nitrogen is supplied to corn from mineralization of soil organic matter or livestock manure, and as N fertilizer, most of which is produced by fixation of atmospheric N (Havlin et al., 1999). N plays a major role in many plant functions, most notably as an essential constituent of proteins, nucleic acid, growth regulators, and chlorophyll (Below, 2002). Fertilizing with N helps to maintain crop growth and development throughout the growing season. But producers need to be mindful of the potential environmental implications of N fertilizers.

The use of chemical fertilizer to provide N to the corn crop accelerated beginning in the 1950s, and this increase did not begin to slow until the 1970s (Keeney, 1982). The rapid increase in the use of N fertilizer resulted in increased N loss to the environment, in the form of higher nitrate concentrations in rivers that drain the Corn Belt, and hence in the Gulf of Mexico (Rabalais et al. 2002). These increased concentrations brought more attention to the need for better stewardship of N management in corn production.

Determining the appropriate rate of fertilizer N application is a critical step in controlling N loss. Nitrogen rate based solely on yield expectation often leads to use of rates that exceed crop needs, bringing increased potential for N loss to the environment. There is a general expectation that N loss can be reduced by increasing nitrogen use efficiency (NUE), which is the efficiency of which applied N to the soil is taken up by plants and not lost to denitrification or leaching (Sharma et al., 2018). Increasing NUE has been accomplished by applying more appropriate rates given by regional guidelines like the maximum return to N (MRTN). The
MRTN approach was developed to consolidate data from recent N response trials, and it uses crop price, N cost, regional soil types, and crop rotation to determine the most appropriate N rate (Sawyer et al., 2005; Sawyer et al., 2006).

Along with N rate, N timing can have a significant influence on N loss depending on the amount of time spent in the soil. The timing of N fertilizer application is variable from farm to farm and especially regionally throughout the Corn Belt. Applying N during the fall, spring (before or soon after planting), or in-season (after crop emergence) all offer advantages and disadvantages. Historically, anhydrous ammonia has often the lowest-cost N fertilizer material, and if applied in the fall, it helps lower the amount of work left until the busy spring. But fall-applied N also brings somewhat higher risk of N loss due to the length of time it is in the soil, and the increased chance of conversion to nitrate and loss by leaching or denitrification before the spring crop can take it up. Warm fall temperatures and mild winters increase the chance for soil bacteria to use the fall applied N as an energy source causing denitrification or nitrification. (U.S. E.P.A., 2002). In contrast, spring application of N lowers the time N spends in the soil before the plant can use it (Blackmer, 1996; Vetsch et al., 2004). Hence spring-applied N often can be used more efficiently than fall-applied N (Welch et al. 1971). Having N available early can help the plant get off to a good start, but the plant does not start rapidly taking up N until V8. These temporal dynamics between soil nutrient supply and crop N demand indicate that applying N closer to when rapid crop uptake is occurring should decrease N loss.

Because applying all of the N before or during planting is often difficult, and because of the recognition that N applied close to the time of crop uptake might be more efficiently used, in-season N applications have gained much attention as one option for providing N when the crop needs it the most. But delays due to weather or other factors in providing in-season N raises the
risk of the crop’s developing N deficiency, which in some cases might result in irreversible yield loss. Along with the timing of in-season application, factors like soil type and drainage, plant health, and subsequent weather all may influence the effectiveness of in-season applications. Walsh et al. (2012) showed that a single application of N made at V10 stage resulted in significant yield loss, but that applying 90 kg N ha\(^{-1}\) before planting meant that the in-season application could be delayed until tasseling without yield loss. In that same study, NUE was maximized when only 45 kg N ha\(^{-1}\) was used at planting and an additional 45 kg N ha\(^{-1}\) was used at either V6 or V10. Higher N rates applied at planting lowered the NUE.

Crop rotations have several benefits, most importantly increases in yields of both corn and soybean \([Glycine\ max\ (L.)\ Merrill]\) when grown in rotation with one another. Sindelar et al., (2016) showed at least 27% lower yields when corn followed corn (CC) compared to corn in in a 2- or 4-year rotation. In most years, corn grain yields were highest when following soybeans. This increase following soybeans can be attributed to a combination of a decrease in net mineralization for CC, and an increase in residual N from symbiotic fixation (Gentry et al., 2001). Corn following corn and corn following soybeans thus respond somewhat differently to N management, with CC typically requiring more fertilizer N, and in some cases showing deficiency symptoms earlier than CS.

The SPAD chlorophyll meter measures chlorophyll content per unit of leaf area, and hence the degree of greenness of a plant’s leaves, which in turn measures relative ability to photosynthesize. Since chlorophyll contains N and requires N (in the form of protein) for its synthesis, the greenness of the leaves also signals the availability of N during prior growth. Late in-season chlorophyll readings have a high correlation with final grain yield (Schepers et al.,
Therefore, chlorophyll meters can be a useful diagnostic tool to measure N availability to the plant.

For producers to adopt new management practices, both the potential benefits and the risks associated with those practices need to be understood and considered. In the case of timing of N application, benefits would come from decreasing N losses, potentially decreasing the amount of N required, and possibly from increasing N uptake and yield. Risks would include being prevented for applying N due to wet weather or inability of applied N to reach the crop’s roots for uptake, and possibly due to formation of N deficiency early such that yield potential is limited. But little research has been done on delaying split or total N throughout the entirety of corn growth and development.

Applying N during the period of rapid growth of corn starting at stage V6-V8 may have potential to increase N uptake, limit N loss to the environment, and increase yield. However, delaying the application of N too long can cause irreversible yield loss. The objective of this study was to measure the effect of delaying N fertilizer application to growth stages ranging from planting to kernel milk stage (R3) on corn N deficiency development (and alleviation) and on grain yield. We further set out to examine whether applying half of the N early and delaying the other half, versus delaying all of the N fertilizer, produced different responses, and whether previous crop—corn or soybean—affects responses to N timing.
Literature Review

Nitrogen plays a crucial role in plant growth and development, being involved in the structure of numerous organic compounds such as proteins, chlorophyll, nucleic acids, and growth regulators. In turn, enzymatic proteins are involved in virtually all synthesis reactions in the cell, making this nutrient one of the most limiting to plant growth in many natural ecosystems. Most soils do not supply enough N to support the high corn crop yields of today, and N fertilizer is required to help meet the N requirements of nearly all the maize grown in the United States (Below, 2002). Besides being the nutrient supplied in greatest quantity by chemical fertilizer applied to corn, N in its nitrate form is also mobile in the soil, and subject to loss by leaching or denitrification, even when managed correctly. This often leads to loss of N to the environment, compromising water quality. It is critically important to manage N to maximize its uptake and to minimize N loss by using the correct N fertilizer rate, timing, placement, and source.

Determining the correct rate and timing is very difficult because of the complex nitrogen cycle that goes on within the soil and environment. Things such as soil texture, temperatures, soil moisture, and soil and N management all affect how much N the soil can provide to the crop. Of the N found in soil, most (>90%) is contained in organic matter and not available to plants until it goes through mineralization (Below, 2002). Even then only 2-3% of the N in organic matter is mineralized to be usable N for plant per year (Below, 2002). Producers need to aware of different soil textures across their farm to make good N management decisions. For instance, soils containing >30% clay have higher responses to applied N then soils that are more course such as sands (Tremblay et al., 2012). Soil types also have a huge impact on potential N loss. Fine textured silty clay loams are more favorable to anaerobic conditions, which can ultimately lead
to denitrification. Leaching losses are generally lower on fine textured soils than coarse textured soils (Welch et al. 1971).

Microbial activity is the means by which organic N is converted to inorganic N, and so the rate of this process depends on soil temperature and moisture. Lower temperature favors the plant uptake of NH$_4^+$, while higher temperature promotes nitrification and the subsequent uptake of NO$_3^-$. This has implications on deciding whether to apply in the fall, spring, or in-season. For instance, high temperatures along with adequate soil moisture within 30 days after sidedress N application allows for much higher uptake (Tremblay et al., 2012). But to determine when the best time to apply N, we need to understand the pattern of N uptake up by the plant throughout its growth and development.

Nitrogen accumulation by the plant is not taken up uniformly throughout the growing season. In the Corn Belt, the rapid period of N uptake starts in mid-June when temperatures are rising, and the crop is growing fast. This rapid increase does not stop until around mid-July when the plant begins to flower. As much as half or more of all N is taken up by flowering (Abendroth et al., 2011; Bender et al., 2012). The peak of N accumulation coincides with the maximum rate of dry weight accumulation, which occurs between V10 and V14 (Bender et al., 2012). Most N management systems provide some N early as plant growth begins, but the early-applied N may not, depending on the amount of N applied, soil conditions, and crop growth, be sufficient to meet the crop’s needs through mid-season, or for the entire season. It is possible that the plant will have to rely on the N from soil mineralization to complete the reproductive stages and to produce full yields. Soil and crop N dynamics later in season are not well-studied, but in-season N applications could be one way to meet N demand while decreasing the risk of N losses (Mueller et al., 2017).
In-season N applications may offer benefits based on the fact that current corn hybrids are taking up a greater proportion of N after silking (Mueller et al., 2016). Having N available late in-season, whether through soil mineralization or through N applications, could allow for less kernel abortion, longer grain fill, increasing kernel size and weight (Ciampitti et al., 2013; DeBruin et al. 2017). With N-efficient hybrids, producers could alter the timing of N applications to increase N uptake by the plant and reduce N loss to the environment.

The issue of negative effects of excessive N usage is not a new problem; it has been researched since the rapid increase in N fertilizer use that began in the 1950s, Since around 1965, more fertilizer N has been added to Illinois soils than is removed in the harvested crops (Keeney, 1982). This has led to investigations of the link between fertilizer use and surface water NO$_3^-$N concentration in Illinois streams and rivers (Keeney, 1982). The Illinois Pollution Control Board conducted hearings and concluded that NO$_3^-$N levels in east central Illinois streams were significantly increased from the use of N fertilizers.

Nitrate loss from fields has negatively affected local ground water, and by moving into surface streams and rivers, has increased the size of the hypoxia zone in the Gulf of Mexico. Since the 1950s, the increase in N fertilizer use follows a trend similar to that shown by increases in nitrate concentration in the Mississippi River. These increases are not only due to increasing use of N fertilizer, but are also influenced by weather and rainfall. Increases to N and phosphorus (P) concentrations have, however, led to an increase in dense growth of algae, and as the algal mats decompose, oxygen is consumed, resulting in an area off the mouth of the river with low oxygen concentration, known as the hypoxic zone, or, in popular parlance, as a “dead zone.” Since 1950 there has been 300% increase in nitrate concentrations in the Gulf (Rabalais et al. 2002), accompanied by a substantial increase in the size (area) of the hypoxic zone. With this
growing concern, producers throughout the Mississippi River basin must be more cautious when managing N fertilizer.

Jaynes et al. (2001) showed that in a corn-soybean rotation, nitrate loss from a tiled field with low (67 kg N ha\(^{-1}\)), medium (135 kg N ha\(^{-1}\)) or high (202 kg N ha\(^{-1}\)) N rates all exceeded the maximum contaminant level (MCL) of drinking water each year that corn was grown. N was only applied to corn, but even in years soybeans were grown the medium and high N rates still exceed the MCL. The economic optimum nitrogen rate (EONR) was calculated to be between the low and medium rate for one of the years and between the medium and high rate the other year. Therefore, it is seen within this study using N rates based on EONR still can lead to excess nitrate loss.

Nitrogen rate guidelines like those generated by the maximum return to N (MRTN) approach help to limit N loss by controlling N rates. N Recommendations that focus only on the relationship between yield and N rate are not likely to be successful since timing, source, and placement all interact with N rate (Morris et al., 2018). Using nitrogen response curves that have been averaged over several locations and seasons may give a good overview, but because of the variability across different locations can lead to inaccurate guidelines (Nafziger et al., 2004).

The MRTN was developed from many N response trials in geographical area and considers crop value, N cost, regional soil types, and crop rotation to determine the most appropriate N rate (Sawyer et al. 2005; Sawyer et al., 2006). In 2017, seven states use MRTN representing 59% of corn grain production in the U.S. (National Corn Growers Association, 2017). MRTN does not provide the exact N rate needed for individual fields, it does provide a rate that will achieve consistently high yields over a given region (Morris et al., 2018). However, the uncertainty of predicting optimum rates can be attributed to water availability, in
relation to soil supplied N and loss to N fertilizer (Morris et al., 2018). Along with controlling N rate, N timing has a significant impact on potential N loss.

Applying fall N allows producer to move hours away from spring and spread them over the fall. However, fall applied N also means the fertilizer N will be accessible to weather and microbes longer than spring applied N. Varying temperatures from year to year makes applying fall N a risk. Warm fall temperatures or even a mild winter could increase microbial activity causing N fertilizer to be more readily converted to NO₃⁻N. Fall applications greatly increase the average of losses, which reduces profits and increases the environmental impact. Even with optimum fall conditions, a warm wet spring conditions can cause N uptake and yield to be reduced by 27% and 20% with fall applied N (Blackmer, 1996). Spring N allows for less time in the soil before the crop needs it allowing for less leaching vulnerability. N recovery was seen to be reduced from 87% for spring N to 45% for fall N (Blackmer, 1996; Vetsch et al., 2004).

In a three-year study, Welch et al. (1971) showed that spring-applied N was more effective than fall-applied N at suboptimal N rates of 67 and 134 kg N ha⁻¹. However, with higher rates of N showed little difference between the two timings. They noted the difficulty in determine the relative effectiveness of fall-applied N given that environmental factors play such a significant role.

Ruiz Diaz et al (2008) found variable responses to applying N in-season. In highly productive soils, they found little response or economic benefit to applying in-season N compared to all-early application. In fact, a medium rate of N (134 kg N ha⁻¹) applied at planting consistently produced higher yield and higher economical return than in-season application of the same amount of N. They concluded that applying pre-plant N, then using a chlorophyll meter
or other canopy sensors to monitor crop health throughout the season, can provide producers confidence in their N management.

Delaying some of the N to in-season application times for corn can in some cases lead to greater N recovery, due to the shorter time that in-season N is in the soil and exposed to potential losses through denitrification, immobilization, or leaching. Scharf et al. (2002) reported no yield reductions from delaying all of the N up to crop stage V11; delaying N until stage V16 lowered yield by 3 percent, while delaying N to R1 lowered yield by 15%. Based on observing such small effects from delaying N, they concluded that it is possible to delay application without penalty, and possibly delaying until the need for supplemental N can be assessed.

Mueller et al. (2017) found that when N accumulation was limited during the vegetative growth, supplemental N at V12 increased total plant N at maturity and increased N recovery efficiency. However, this increase in plant N at maturity failed to increase grain yield. They concluded, however, that there may be potential for late application to lead to less loss of N.

Delaying the second application of split applied N can cause yield loss that cannot be overcome by added N. Walsh et al. (2012) showed that if pre-plant N was applied, the second application could be applied as late as tassel without yield loss, but if application of all of the N was delayed, yield was lowered; some N was needed early in the growing season for full yield. If no preplant N was applied, yield was lowered significantly if N was not applied until V10. Split applications with pre-plant N showed significantly increased yield compared to treatments without pre-plant N. Delaying a sidedress application, if some N is applied early, might allow producers to make plant nutrient evaluations to improve N management decisions.

Jokela and Randall (1989) found that there was no positive effect of delayed N on dry matter yield or N uptake, and they found higher amounts of residual NO₃-N after harvest from N
applied at V8 compared to N applied at planting. The ability for the plant to use late applied N depends on environmental conditions. If moisture is limited, the plant may show little response to N applied in-season.

Binder et al. (2002) ran an experiment in Mead, NE to examine maize response to supplemental N based on the level of N deficiency. Five N rates ranging from 0 to 220 kg N ha\(^{-1}\) were used as an initial N application, and supplemental N was added after a certain sufficiency index (SI) was reached. The SI was calculated based on the relationship between N deficient and non-N deficient chlorophyll readings. Hence, greener the leaves are assigned a higher SI number compared to N deficient leaves. Delaying N until V6 resulted in a SI was below 0.90, and resulted in a 12% yield decrease, indicating that N deficiency can be too severe to prevent full recovery when supplemental N is added. Grain yield increased as late as R3 for N-deficient corn, but did not reach maximum yield levels. When maize had SI values of 0.95, 0.85, 0.75, or 0.65, yield decreased by much as 8, 19, 42, and 78 kg grain ha\(^{-1}\) per day, respectively, as N application was delayed. Although late-season N application to N-deficient maize will not often recover full yield, it may still increase yield some, depending on the severity of the N deficiency.

The predominant crop rotation in the Corn Belt is corn following soybean in a two-year rotation (CS). Although economics affect the amount of continuous corn a producer might grow, the corn-soybean both generally increases the yields of both crops, and with no N fertilizer needed for soybean and less N needed for corn following soybean (Gentry et al., 2001), the rotation can lower the carbon footprint of the production system. Sindelar et al. (2016) showed that at least a 27% yield decrease was seen for corn following corn (CC) than in a 2- or 4-year rotation. High residue loads on the soil surface can cause cooler and wetter soil, decreasing the amount of mineralized N available for the crop (Sindelar et al., 2016). For these reasons, N
deficiency appears earlier and can be more severe for corn following corn than for corn following soybeans.

Monitoring crop health can be a useful tool for producer when applying delayed or in-season N applications. Tools like chlorophyll meters, aerial imaging, soil tests, or active canopy sensors all can help determine prior N availability and the current health of the crop. The SPAD 502 was compared to several active sensor indices and showed it was at least equal or more capable of measuring N stress (Barker et al., 2008; Blackmer et al., 1994).

The SPAD meter can be a very useful tool to aid with in-season nitrogen application. The SPAD meter gives quick and easy results for the “greenness” of plant leaves. But taking SPAD measurements during early vegetative growth can lead to low reading that can be unreliable. SPAD reading taken at an early vegetative stage are often due to lack of leaf thickness, and to weather and soil effects on young corn plants (Bullock et al., 1998; Piekielek et al., 1992). Using SPAD later in vegetative growths in conjunction with a sufficiency index can help determine if or how much additional N needs to be applied to the deficient corn (Binder et al., 2002).

Chlorophyll (SPAD) readings taken at R3 can usually be a good indicator of how the plant will yield (Schepers et al., 1992; Scharf et al., 2006; Blackmer et al., 1994). This reading can determine the amount of N the plant was able to take up prior to the R3 growth stage. A plant with a higher reading means it has taken up enough N to support high photosynthesis rates late in the growing season during grain fill. In contrast, a lower SPAD reading at R3 could indicate not enough N was available throughout the growing season, meaning the plant may have had to remobilize more N within the plant during grain fill.
Materials and Methods

Field experiments were conducted from 2015 to 2017 at the University of Illinois Crop Sciences Research center near Urbana, Illinois (40.04707; -88.225264) on Flanagan silt loam soils. Monthly precipitation for each year as well as 30-year averages are in Table 1. Trials were planted at the seeding rate of 89,000 seeds ha\(^{-1}\) using Pioneer P0987 AMX in 2015, and Pioneer 1197 AMX in 2016 and 2017. Tillage consisted of fall primary tillage using a disk-ripper, followed by a soil-finisher prior to planting. Plots consisted of four, 0.76-m rows 11 m in length. Trial maintenance consisted of both pre-emergence and post-emergence herbicides and hand weeding as needed.

Separate trials were conducted each year in corn following soybean and corn following corn. Trials were in adjoining or nearby fields, with similar topography, productivity, and soil type. Each trial was laid out as a randomized complete block design (RCBD) with four blocks. One set of treatments consisted of 112 kg N ha\(^{-1}\) applied as UAN (28-0-0) solution injected between the rows at planting, followed by a second increment of 112 kg N ha\(^{-1}\) applied at growth stage V3, V6, V9, V12, V15, VT/R1, R2, or R3. One treatment consisted of 112 kg N ha\(^{-1}\) only, with no additional N. The second set of treatments consisted of 224 kg N ha\(^{-1}\) applied as injected UAN at planting, or delayed to the same eight stages listed above, ranging from V3 to R3. All applications made after planting (beginning at V3) were made by using a backpack CO2-pressurized sprayer with a 2-nozzle boom that streamed the N near the base of the plants in the row. The center two plot rows were harvested for yield using a plot combine, and yields were adjusted to 15% moisture.
In 2015, we took SPAD readings beginning the stage after N application and subsequently at each succeeding application date on these plots. In 2016 and 2017, we took readings on the plots at the time of each delayed N application, and subsequently at each application timing on all plots to which delayed N had been applied. Readings were taken on the uppermost collared leaf until stage V15, and on the leaf subtending the ear shot or ear at stage VT/R1 and later stages. Readings were the average of measurements on 14 plants in the center two rows.

Statistical analysis for this experiment utilized PROC MIXED and PROC UNIVARIATE in SAS to determine normality and homogeneous variance within the experiment. PROC MIXED was used to calculate least significant means for yields and compare significance between treatments. PROC ANOVA was also used to calculate least significant differences in SPAD data. Year was treated as random when analyzing over years. Treatment was considered fixed, and block and residual random.
Results and Discussion

The 2015 growing season was close to normal except for the very high rainfall (229 mm, more than twice the normal) in June (Table 1). The crop was well-established by this time, and crop growth and yields were close to normal; the Champaign county yield in 2015 was 11.9 Mg ha\(^{-1}\) (NASS). Wet soils in June likely influenced soil nitrogen dynamics, and the field where corn followed soybean had less slope than where corn followed corn, and so was more affected by brief periods of standing water. Temperatures and rainfall, and crop growth and yield, were close to normal in 2016, and county average yield was 13.2 Mg ha\(^{-1}\). The 2017 growing season was characterized by cool, wet conditions in late April and early May, then relatively dry conditions for the remainder of the growing season, and above-normal temperatures in July. Even so, yields in 2017 were like those the previous two seasons, with a county average yield of 13.0 Mg ha\(^{-1}\). It’s likely that the limited rainfall after the wet May weather helped to stimulate mineralization, limit N loss and foster good root growth.

**Corn following soybeans**

Averaged over three years, yields of corn where corn followed soybean (CS) exceeded 14.5 Mg ha\(^{-1}\) for the treatments that received N during early vegetative growth (Table 3). The yields obtained from delays in applications of the second increment of N only if the second application was delayed until the last application timing at R3, which yielded 9% less than the average of yields produced by earlier applications (Table 3). The single application of 112 kg N at planting yielded less than any of the treatments receiving 224 kg N split, so adding N late produced more yield than not adding the second increment N at all.
Applying all 224 kg N at planting resulted in 6% lower yield compared to application of all the N at V3, and 9% lower yield than applying all the N at stage V6 (Table 3). One possible explanation for this is that the N injected (between the rows) at planting was not as immediately available to the young plants as was the N applied near the row at these later stages. Given the fact that we did not see this yield loss when half the N was applied at planting, it may be that early N deficiency, perhaps related to low plant-available N near the nodal roots as they begin to develop, might have lowered the yield potential.

Delaying all the N to V15 did not result in lower yields than when all of the N was applied at V3. This result is somewhat surprising, given the fact that roughly half of the N taken up by the corn crop is taken up by stage V15 (Abendroth et al., 2011; Bender et. al., 2012.) With high amounts of organic N in the soils on which these experiments were conducted, the release of perhaps 120 kg N ha$^{-1}$ (representing half the uptake at these yield levels) by late June is certainly possible. Yield began to decline as application of all of the N was delayed past V15: compared to the yield from applying all the N at V3, yield was decreased by 12% when all of the N was applied at VT/R1, by 19% when all was applied at R2, and by 37% when all of the N was applied at R3. Comparing this decline with the yield from applying only 112 kg N ha$^{-1}$ at planting indicates that the soil supplied about 100 kg of N to the crop if left unfertilized until between R1 and R2, and although we did not include a zero-N treatment, results from nearby N rate trials indicated that applying all of the N at R3 likely produced about the same yield as using no fertilizer N at all. The recommended MRTN is about 200 kg N ha$^{-1}$ for CS in central Illinois, and our use of a higher N rate than this might have diminished some of the timing effect that we might have seen at lower N rates.
Delaying the application of the second increment of N in CS produced similar results all three years, even though yield levels were substantially higher in 2016 than in 2015 and 2017 (Table 3). When application of all of the N was delayed, however, responses were less consistent. In 2015, delaying all of the N did not produce a significant yield reduction until the R2 application, but yields then dropped quickly, to 22\% less than yield with all N applied at planting at R2, and 27\% less at R3. In 2016, the drop in yield began earlier, with 4\% less at the V12 application, to 37\% less if all of the N was delayed to stage R3. In 2017, delaying all of the N until V9 produced a lower yield than application at V6, but yields were stable with further delays up to VT/R1. Further delays decreased yields: application at R2 decreased yields by 13\% and application at R3 decreased yield by 26\% (Table 3).

**Corn following corn**

Yield levels in corn following corn (CC) trials were comparable to those of CS in 2016 and 2017, but in 2015 the average yield of CC was more than 25\% lower than for CS (Table 4). Even so, the relative responses to delayed N application were similar in 2015 and 2016, so we combined the analysis over these two years. Across these two years, yields with half of the N applied at planting and half delayed did not decrease until the delay extended past VT/R1. Even then, yield decreases were modest, with yields from delaying the second increment of N to R2 and R3 both only 7\% lower than the yield when the second half of the N was applied at stage V3 (Table 4). This loss was mostly due to the response in 2015; in 2016, yields from delaying half of the N until R2 or R3 were not much significantly lower than those following application of the second increment of N during vegetative stages.
As we noted for CS, applying all 224 kg N at planting yielded less than when all the N was applied at V3 (Table 4). In CC, however, this occurred only in 2015, when applying the N at planting yielded 21% less than applying at V3. In neither 2016 nor in 2017 was there any difference between yields from N applied at planting and from N applied at V3. These results do not lend support to the hypothesis, advanced above, that early lack of N near the nodal root system might decrease yield potential. Some heavy amounts of rain fell in both early and mid-May in 2015, and it is possible that mineralized N might have been moved away from the root zone. But previous crop residue would have been expected to slow net mineralization some, and it is not clear why corn following corn would have been less prone to this than corn following soybean in 2016 and 2017.

When all the N was delayed, the onset of yield loss over the 2015 and 2016 trials in which corn followed corn began earlier and accelerated more quickly than in corn following soybean (Table 4). Using as a base the average of yields from applications made at V3, V6, and V9, the decline in yield was 11% with application at V12, 14% at V15, 29% at VT/R1, 43% at R2, and 49% at R3 (Table 4). In contrast, in corn following soybean this decline was only 13% at VT/R1 and 38% at R3 (Table 3). The yield with all N delayed to VT/R1 was similar to the yield with 112 kg N applied at planting, as we also found in corn following soybean. As was the case in corn following soybean, we expect, based on nearby trials in these fields, that the yield with all of the N delayed to R3 was likely little different than the yield had there been no N fertilizer applied at all.

In comparison to results in 2015 and 2016, delaying half of the N had no significant effect on corn yield in 2017; with 112 kg N at planting, applying the second 112 kg N at R3 produced the same yield as applying the second increment of N at V3 (Table 4). Delaying all 224
kg N until V15 decreased yield by about 12% compared to applying all of the N at V3 but applying at VT/R1 and R2 did not decrease yields further, and the yield following application at R3 was only 20% less than when all of the N was applied at V3 (Table 4). We also saw no yield decrease from applying all the N at planting compared to applying it at V3, unlike the large difference in 2015. It seems likely that the dry weather during July and August helped to preserve the soil N, and possibly helped to keep roots healthy and functional at depth, allowing the crop to take up mineralized N more efficiently than in other trials in this experiment. In this regard, corn following corn behaved much more like corn following soybean in 2017 than in the other years.

Even with less rain late in the 2017 growing season, yields in CC decreased less with delays in N application than in the previous two years. This may be attributable to having more mineralized N throughout vegetative growth in 2017. Yield responses to delayed N, particularly when all of the N was delayed, are of course influenced by the amount of N available from the soil via N mineralization, along with retention of this N and availability to the crop. Late in-season applications when surface spoil moisture is limited may limit the amount of applied N that become available to the crop, limiting the yield response to late N.

The productive soils in this experiment may have allowed for a longer delay without large yield losses compared to those in soils with less organic matter and, perhaps, less water-holding capacity. Scharf et al. (2002) and Walsh et al. (2012) found that applying all of the N could be made only as late as stage V10 or V11; later applications resulted in significant yield loss. This ability of higher-OM soils to sustain yield potential longer may only come from more mineralization, but also the potential of current hybrids ability to take up N from the soil. In any case, it is clear that, especially when half of the N has been applied early, producers in
productive soils like Flanagan silt loam have additional time to apply N before significant yield
is lost from not having N applied at an earlier stage.

**SPAD**

Chlorophyll meter (SPAD) readings taken in 2016 and 2017 provided a valuable look at
how N deficiency developed over the course of the season, and how the crop responded to
application of delayed N. The SPAD data from 2016 will serve to illustrate the usefulness of
these data.

Chlorophyll meter (SPAD) readings for CS and CC taken at the R3 growth stage over all
treatments (2016-17) showed a high, positive correlation with yield ($R^2=0.87$, Figure 10) and
($R^2 .8736$, Figure 10) respectively. 2016 SPAD readings at R3 positively correlated well with
yield for both CC ($R^2=0.91$) and CS ($R^2=0.95$), over both split and one-time applications.
However, 2017 SPAD readings at R3 only moderately correlated with yield for CC ($R^2=0.59$)
and CS ($R^2=0.79$). Like what was seen with yield CC had less response with delayed N which
cause less yield variability which caused the low $R^2$.

In treatments where N was applied at planting, plants reached SPAD readings of 50 as
early as V9 for both CS and CC (Figure 7 and 8). When total N was delayed, 2016 CC never
reached a SPAD reading of 50 (Figure 7 and 8) while CS 2016-17 and CC 2017 did (Figure 1, 2,
4, 5, 7, 8, and 9). Absolute SPAD values were lower in CC than in CS, even though both crops
produced similar yields in 2017.

The plant’s ability to regain greenness has large implications regarding the effectiveness
of in-season N applications. Regaining greenness shows the plants ability to recover from a N
deficiency and potentially increase grain yields. In CS delaying the second application of the 112
kg N had no effect on R3 SPAD readings or the ability for the plant to increase its greenness. However, in 2016 CC with N applied at planting, the plant was able to regain greenness if second increment was applied before V15 and began significantly decreasing if the second increment was delayed further (split application at VT/R1 was not significantly less). For 2017 CC, with N applied at planting, the plant was able to regain greenness if the second increment was applied by V15. Having some N at planting allowed in most cases plants to regain greenness as long the second increment was applied by late vegetative stages.

In both CC and CS delaying total N past V9 meant leaf greenness began to decrease. However, applying total N by V12 meant the plant could regain greenness and was not a significantly lower SPAD reading than when N was split at V12. Although greenness was recovered, yield was still significantly reduced when total N was applied at V12 than with a split application at V12. Delaying total N past V15 did not regain total greenness (significantly less than the split application at V15) and that related to significant loss in yield as well. Although plants continued to lose greenness the later total N was delayed, yield showed that the 224 kg N ha\(^{-1}\) applications past V15 still significantly increased leaf greenness and yield, but significantly less than the highest yield.

For CC in 2017, the lowest SPAD reading was taken at V15. Following V15 SPAD reading began to increase even with no N applied (Figure 9). This is a different response then what was seen with CS and CC in 2016 (Figure 1, 2, 4, 5, 7, and 8). SPAD reading taken at R3 for CC 2017 were higher than (not significant) the R3 SPAD readings taken for CS. This can help explain the unusual high yield with total N delayed past flowering for CC.
Summary

Our findings in this study are in agreement with previous research showing the importance of having at least some available N early in the crop’s growth in order to maximize yields. However, since N applied at planting was injected between rows, it could be argued that a higher response to N applied before the V6 treatment (i.e. planting and V3) might have been seen if N was broadcasted or banded to give the plant the opportunity for earlier access. Consistent with previous reports, the relationship between SPAD and yields indicates that N applied earlier to N deficient corn allows for higher recovery.

Late-applied N (VT and later) showed limited (but not zero) effect on overall yield if only 112 kg/ha was applied at planting. Having 112 kg of N applied at planting allowed for a delay in the second application of 112 kg of N as late as R3 for corn following soybean and R2 for corn following corn. With no N applied at planting, the application of all 224 kg needed to be applied by VT/R1 for corn following soybeans and by V12 for corn following corn. Compared to corn following soybean, corn following corn loses yield earlier and more rapidly the longer N is delayed. Although having some N upfront can limit the amount of yield loss for corn following corn.

Leaf chlorophyll (SPAD) readings taken at R3 showed a strong correlation with yield when it is taken and R3. For both corn following corn and corn following soybeans, having N applied at planting meant the plant was able to maintain its healthy green color if the second N application was made by R3. Delaying total N meant the plants greenness began to decrease if delayed past V9. While delaying total N meant that N had to be applied by before V15 for the
crop to completely regain plant greenness for both corn following corn and corn following soybeans.

Greater response to delayed N would have likely been seen in soils with coarser texture, very high clay content, or with lower organic matter, all of which would increase the chances of N loss. Split-applied N applications would have likely shown higher response if applied to crops with limited root growth due to soil conditions. The highly productive soils on which we ran these experiments likely the response to delayed N; all-early N application commonly produced the highest yields, indicating a good supply of N from soil mineralization along with what we expect was limited N loss. This means that applying in-season or delayed N will have little benefit to producers in productive soils. Future projects need to be conducted with varying N rates to determine whether a lower rate of N would be enough to maximize grain yields.
### Tables and Figures

Table 1. Monthly precipitation and average monthly temperatures during the 2015-2017 growing seasons at Champaign, along with the 1980-2010 normal values. Data from the Illinois State Water Survey and NOAA.

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Table 2. Application dates for corn following corn and corn following soybeans for 2015-17.

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<td>16-Jun</td>
<td>15-Jun</td>
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</tr>
<tr>
<td></td>
<td>V12</td>
<td>24-Jun</td>
<td>22-Jun</td>
<td>29-Jun</td>
</tr>
<tr>
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<td>V15</td>
<td>1-Jul</td>
<td>28-Jun</td>
<td>6-Jul</td>
</tr>
<tr>
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<td>13-Jul</td>
</tr>
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<td></td>
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<td>1-Aug</td>
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<td>29-Jul</td>
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Table 3. Yields of corn following soybean as affected by timing of nitrogen application, Urbana, Illinois. Means are separated at p=0.1.

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<td>+ 112 kg N</td>
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<td>15.5</td>
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* Received only 112 kg N ha\(^{-1}\); no additional N applied.
Table 4. Yields of corn following corn as affected by timing of nitrogen application, Urbana, Illinois. Means are separated at p=0.1.

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* Received only 112 kg N ha⁻¹; no additional N applied.
Figure 1. SPAD readings in corn following soybean with split N in 2016. Readings begin at the time of initial application of N to that treatment and are taken at each subsequent stage through R3.
Figure 2. SPAD readings in corn following soybean with N applied once in 2016. Readings begin at the time of initial application of N to that treatment and are taken at each subsequent stage through R3.

Corn following soybeans, all N at once, 2016

SPAD reading

Corn stage

V3 V6 V9 V12 V15 R1 R2 R3
Figure 3. Correlation between SPAD reading at R3 and corn grain yield of corn following soybeans, 2016. Linear correlation coefficients were $r = +0.97$ for single N application and $r = +0.65$ for split N application.
Figure 4. SPAD readings in corn following corn with split N in 2016. Readings begin at the time of initial application of N to that treatment and are taken at each subsequent stage through R3.
Figure 5. SPAD readings in corn following corn with N applied once in 2016. Readings begin at the time of initial application of N to that treatment and are taken at each subsequent stage through R3.
Figure 6. Correlations between SPAD readings at R3 and corn grain yields when N was split-applied or applied all at once, corn following corn, 2016.
Figure 7. SPAD (leaf chlorophyll) readings of corn following soybeans, 2016-17. Solid lines are readings at the time of application of the second increment (112 kg) of N and of all 224 kg of N, while dashed lines show SPAD readings at stage R3.
Figure 8. SPAD (leaf chlorophyll) readings of corn following corn 2016. Solid lines are readings at the time of application of the second increment (112 kg) of N and of all 224 kg of N, while dashed lines show SPAD readings at stage R3.
Figure 9. SPAD (leaf chlorophyll) readings of corn following soybeans, 2017. Solid lines are readings at the time of application of the second increment (112 kg) of N and of all 224 kg of N, while dashed lines show SPAD readings at stage R3.

Corn following corn, 2017

LSD 0.10: 1.8

SPAD reading

Stage at application of delayed N

Plant V3 V6 V9 V12 V15 R1 R2 R3

Figure 9. SPAD (leaf chlorophyll) readings of corn following soybeans, 2017. Solid lines are readings at the time of application of the second increment (112 kg) of N and of all 224 kg of N, while dashed lines show SPAD readings at stage R3.
Figure 10. Correlation between SPAD reading at R3 and corn grain yield, 2016-17. Linear correlation coefficients were $r = +0.75$ for corn following soybeans and $r = +0.76$ for corn following corn.
Figure 11. Percent maximum yield in relation to delay in N as measured by modified growing degree days, 2015-17


