NITROGEN PLACEMENT CONSEQUENCES IN AT-PLANT AND IN-SEASON APPLICATIONS FOR CORN RESPONSES AND NITROGEN EFFICIENCIES

by

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A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science

Department of Agronomy

West Lafayette, Indiana

May 2020

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Dedicated to my wife, Courtney K. Thompson

ACKNOWLEDGMENTS

A special thank you is necessary for my advisor, Dr. Tony Vyn, for not only mentoring me over the last two and a half years, but also for taking a chance on me and believing that I had what it takes to complete this degree. Tony has always pushed me to my limit, making me a better person, agronomist, and scientist. I am very grateful to have been his student. Also, I want to thank my committee members, Dr. Robert Nielsen, Dr. Shalamar Armstrong, and Dr. Bradley De Van Woestyne for input and guidance during my studies.

Thank you, Dr. Keith Johnson, for allowing me to teach Forage Management. Through that experience, Keith became a mentor and friend. I have enjoyed our many conversations about forages, life, and graduate school.

Thank you to the Cropping Systems team, especially current students, Lauren Schwarck, Garrett Verhagen, Lia Olmedo Pico, Quincey Tuttle, and Monica Olson, along with graduates of the team Sarah Mueller and Heather Pasley for their long hours collecting data and most importantly friendships. Jason Lee is a very good friend and individual who encouraged me to continue my education, thank you!

To my parents, Mark and Annette Thompson, thank you for instilling hard work and determination in me; without those qualities, I wouldn't be the agronomist and son I am today. Thankfully my father Mark was bold enough to start a row-crop farm in the 21st century. Without the family farm experience, I likely wouldn't have joined FFA or be in the career that I am.

To my siblings Kyle, Hanna, Mike, and Megan, thank you for the support during both undergraduate and graduate school. To all my friends at Purdue, both undergraduate and graduate, the experiences gained and memories made will be cherished for a lifetime.

Thank you to my FFA family, Steve and Letty Stauffer, who taught me competitiveness, leadership, and soil judging which brought me to Purdue. The competitiveness and determination inside of me from experiences in FFA are part of the reason I continued my education and continue to work hard to better myself.

Finally, to my wife Courtney. Without your love and compassion I would not have been able to make it through long field days, stressful nights, or boring weekends living in the "city". Also, thank you for proofreading my writing and always adding tons of commas!

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ABSTRACT

Selection of optimum nitrogen (N) fertilizer timing, rate, and placement strategies by corn (*Zea mays* L.) producers are among their most important annual management decisions. Much research has been conducted on pre-plant, at-plant, and one or more sidedress timings for N application to corn, but few public-sector studies employ modern technological approaches for N placement in their experimental designs. Research gaps on optimum placements for at-plant N systems are especially acute when N banding quantity exceeds 20% of the intended season-long N rate. Previous sidedress research has rarely utilized modern N placement tools with high clearance delivery devices for early and late in-season sidedress timings when >50% of the season-long N rate was already applied at planting. Therefore, this 2017 and 2018 Indiana-based field research addressed three questions i) are corn planters that deliver 50% to 100% of a full-season N rate at traditional or alternate band placements capable of matching or exceeding grain yields achieved by lower starter fertilizer N rates, ii) what is the impact of split N management on grain yield and/or N fertilizer recovery efficiency (NRE) when ≥50% of the total N rate is supplied at-plant, and iii) do alternate sidedress N placements (i.e. soil-surface streaming versus injection versus broadcast at multiple timings) in split-N sidedress applications influence grain yield and aboveground plant recovery of N fertilizer?

To evaluate the consequences of moderate to high N rates banded at planting, urea-ammonium nitrate (UAN) was coulter-banded with a prototype Deere DB20 row-crop planter as close as 5cm x 5cm (5x5) (distance from soil surface x distance from seed row) to as far as 10x20 at planter applied N rates of 34, 101, and/or 202 kg ha^{-1}. These at-plant applications were followed by a V5 to V6 stage mid-row sidedress application (if required) to achieve a uniform total N rate of 202 kg N ha^{-1}. Analyses were primarily focused on 5x5 and 10x5 starter band positions as these were the only placements represented at the 34 kg N ha^{-1} rate. In these placement comparisons, 5x5 banding yielded similarly to 10x5 banding in 2017, but increased yield 6.6% (averaged across 34, 101, and 202 kg N ha^{-1} rates) in 2018. Corn grown in 2018 with at-plant rates of 101 and 202 kg N ha^{-1} produced grain yields statistically similar to or greater than that obtained with the 34 kg N ha^{-1} rate (averaged across 5x5 and 10x5 placements). In 2018, the 101 kg N ha^{-1} rate increased yields by 14.8% and NRE by 18.5 g g^{-1} compared to banding of 34 kg N ha^{-1}. A secondary analysis included 6 placements (5x5, 5x13, 5x20, 10x5, 10x13, and 10x20) at just the 101 and 202 kg N

ha^{-1} rates. Among these additional placement treatment combinations (averaged across 101 and 202 kg N ha^{-1} rates), both 5x13 and 10x20 banding reduced grain yield in 2018 by 12.5% and 10.1%, respectively, when compared to 5x5 banding. No yield differences among these 6 at-plant placements were found in 2017. Therefore, moderate to high N rates can be banded safely at-planting with the typically close starter fertilizer placements, but higher NRE and optimum yields can be achieved when a 50:50 split N fertilizer management approach is used.

The optimal sidedress experiment targeted placement and/or timing impacts on corn yields and NRE when at-plant N was ≥50% and sidedress N was ≤50% of the total N rate. Single at-plant (AP) applications at total N rates of 26 (Zero), 112 (AP_112) and 224 (AP_224) kg N ha^{-1} were compared to split applications of 202 kg N ha^{-1} (with ~55% of total N applied at-plant plus the balance at sidedress). Sidedress N was applied at V5 or V12 timings with surface streamed versus subsurface injection of UAN, or via high-clearance broadcasting of urea at the V8-stage. In nearly every split sidedress approach, apart from the V12 injection treatment in 2017, grain yields and NRE with split-N sidedress responded similarly to AP_224 each year despite the reduced total N rate at 202 kg N ha^{-1}. Both V12 streaming and AP_224 yielded 6.7% more than the V12 injection approach in 2017. The reduced yield in 2017 from late-season injection contributed to the 4.6% grain yield gain for surface-streaming applications (averaged across timings) with no apparent NRE advantage.

These responses confirmed that in-season sidedress N placement influenced yield and, in our case, the surface-streaming advantage over injection was most evident at V12 where late vegetative to flowering rainfall was plentiful. Similarly, planter N placement was not influenced by N band depth as much as by N band distance from the seed row where 13 and 20cm distances occasionally decreased yield in 2018. This research provided evidence of modern placement technology impacts at planting and sidedress times where UAN placed near corn seeds in the seed-furrow and/or plants in the row never reduced, and occasionally increased, grain yield and/or N recovery in corn cropping systems.

CHAPTER 1. FOUR R'S OF NITROGEN STEWARDSHIP IMPACTS ON IN-SEASON PLANT RESPONSES AND GRAIN YIELD IN CORN

1.1 Introduction

Corn (*Zea mays* L.) is one of the most widely produced cereal crops in the world. The top three corn-producing countries are the United States (U.S.), China, and Brazil, respectively (FAO, 2020). In 2017, the U.S. produced nearly 1/3 of the global corn crop (FAO, 2020), with Indiana producing 1/15 of the U.S. crop on 2.1 million hectares (USDA-NASS, 2020). On average, Indiana produces 11.3 Mg ha^{-1} compared to global production of just 5.8 Mg ha^{-1} (USDA-NASS, 2020; FAO, 2020). In 2017, Indiana ranked 5^{th} nationally in total U.S. corn production (USDA-NASS, 2020). However, Indiana corn production area has decreased in 2019 compared to earlier cropping years, likely a contribution from reduced commodity prices, development, and alternative crops providing potentially more net income per unit land area are being grown (USDA-NASS, 2020).

Producing high yielding corn is dependent on inorganic nitrogen (N) fertilizer sources. Agricultural use of fertilizer N in the U.S. reached 12 million metric tons in 2017 and U.S. nitrogen fertilizer consumption was only surpassed by China who consumed nearly 30 million metric tons (FAO, 2020). In 2017, agricultural N sources in the U.S. were primarily urea ammonium nitrate (UAN), urea, and anhydrous ammonia with a national use of 10.6, 6.3, and 3.5. million metric tons, respectively (FAO, 2020).

Inorganic N fertilizer use did not begin until 1913 as commercial sources of N were not widely available until the development of the Haber-Bosch process of converting N_2 gas into ammonia (NH_3) by high heat and energy (Mosier et al., 2004). Although the U.S. ranked second in N consumption in 2017, historically from 2002-2016, the U.S. ranked third in global N consumption with China and India taking the number one and two spots, respectively (FAO, 2020). From 2002-2016, global consumption of N increased by 1.8 million metric tons $year^{-1}$ in the U.S. Although fertilizer N is one of the highest nutrient input costs for corn growers, N remains the most widely applied nutrient globally (Masclaux-Daubresse et al., 2010). The importance of N on modern production agriculture is well known; N is often the most limiting variable behind water in reducing crop growth and yield. Improving our use of N in production agriculture could prove vital in global food security (Gaffney et al., 2019).

1.2 N Uptake in Corn

Plant available N is mostly taken up as dissolved nitrate (NO_3^-) and ammonium (NH_4^+) (Brady and Weil, 2009). Approximately 2/3 to 3/4 of total plant N uptake occurs by R1 with peak N uptake at or after V10 (Hanway, 1963; Mengel and Barber, 1974; Abendroth et al., 2011; Bender et al., 2013). Bender et al. (2013) observed peak N uptake of 7.8 and 8.9 kg N ha^{-1} day^{-1} occurred between V10 to V14. While peak N uptake occurs in the late vegetative growth stages, N uptake continues post silking. Post silking N can account for >1/3 of the total N uptake (Pan et al., 1986; Mueller and Vyn, 2016) and is responsible for 30 to 70% of grain N contributions (Masclaux-Daubresse et al., 2010).

1.2.1 N Fertilizer Efficiencies

The derivation of N efficiency metrics such as N use efficiency (NUE), N recovery efficiency (NRE), and N internal efficiency (NIE) are shown in Eq. 1 to 3 below.

$$\text{Eq. [1]} \quad \text{NUE} = \frac{\text{GY}_{\text{Nfert}} - \text{GY}_{\text{Nunfert}}}{\Delta_{\text{N applied}}}$$

$$\text{Eq. [2]} \quad \text{NRE} = \frac{\text{TNU}_{\text{Nfert}} - \text{TNU}_{\text{Nunfert}}}{\Delta_{\text{N applied}}}$$

$$\text{Eq. [3]} \quad \text{NIE} = \frac{\text{GY}_{\text{Nfert}} - \text{GY}_{\text{Nunfert}}}{\text{TNU}_{\text{Nfert}} - \text{TNU}_{\text{Nunfert}}}$$

In the equations above, GY_{Nfert} is the grain yield of plots receiving N, $GY_{Nunfert}$ is the grain yield of non-or low fertilized control plots, TNU_{Nfert} is the total N uptake in above ground biomass of N fertilized plots, $TNU_{Nunfert}$ is the total N uptake in above ground biomass in the non- or low-fertilized control plots, and $\Delta_{Napplied}$ is the difference in fertilizer rate from the N fertilized plot and the non- or low-fertilized plot.

Nitrogen recovery efficiency is a measurement of the plant's ability to recover applied fertilizer into the above-ground biomass (stover) (Moll et al., 1982). Nitrogen fertilization rates greater than plant needs reduce NUE (Raun and Johnson, 1999). Mueller et al. (2017) found increased NRE with split N applications where the majority of N was supplied near planting and the remaining 45 kg N ha^{-1} was delayed until V12 to 14 without consistent increases in grain yield.

Advancements in breeding and genetic selection have improved plants' ability to recover N, Mueller et al. (2019) proved this utilizing popular historic and modern hybrids from 1946 to 2015; researchers found a consistent increase in NUE, NRE, and NIE as hybrids progressively modernized.

1.2.2 Management Impacts on N Recovery Efficiency

The 4 R's of nutrient stewardship (Nutrient Stewardship, 2017) promotes using the right source, rate, time, and placement of fertilizers. Each "R" reflects various agronomic management practices that influence the plants' ability to recover or use fertilizer. The principal driver behind NRE is the total N rate applied as fertilizer loss is reduced with low application rates (Russelle et al., 1981; Wortmann et al., 2011; Abbasi et al., 2012). In a review of experiments reporting both NRE and N_2O losses from North America, Omonode et al. (2017) found mean NRE to be greatest (≥100%) when N was supplied <60 kg N ha^{-1} and that NRE decreased quickly (to ~60%) as N rate approached 100 kg N ha^{-1} before leveling off (<60%) around 150 kg N ha^{-1}. Agreeing with Omonode, Wortmann et al. (2011) found NRE to be >80% at 56 kg N ha^{-1} and near 40% at 280 kg N ha^{-1} in a corn-soybean rotation in Nebraska, further proving the impact total N rate has on NRE. In addition, both Omonode et al. (2017) and Burzaco et al. (2013) found gaseous N losses increased with N rate, thus reducing the potential for N recovery by corn plants. Agronomic optimum N rates for continuous corn yield are between 235-295 kg N ha^{-1} among regions in Indiana (Camberato and Nielsen, 2019), the high N rates employed in Indiana strongly reduce the opportunity to maintain optimum NRE levels in these corn production systems.

With agronomic optimum N rates typically exceeding preferred rates for maximizing NRE, researchers have experimented with nitrification inhibitors at commonly employed N rates and their influence on NRE. Nitrification inhibitors generally reduce N loss by temporarily inhibiting nitrification, thus theoretically improving NRE. Researchers Omonode and Vyn (2019) treated UAN with an inhibitor and increased NRE by 10% compared to non-inhibited UAN at 220 kg N ha^{-1} in Indiana. Drury et al. (2017) showed that N loss from broadcast urea (N applied at 130 kg ha^{-1}) could be reduced when urea was treated with a urease inhibitor; inhibitors also reduced N loss in injected UAN and was associated with an increase in grain yield over non-inhibited injected UAN. Similarly, Jaynes (2013) observed that N fertilizers with inhibitors added reduced gaseous losses across N timings (V2, split between V2 and V6, and split between V2 and V12) and across total N rates (134 kg N ha^{-1} at all three timings or 202 kg N ha^{-1} at V2).

Along with total N supplied, adequate water supply is essential for nutrient uptake to occur; knowing this, Oberle and Keeney (2013) found NRE to be greater (30-40%) in irrigated sandy loams over rainfed silt loams (15-30%) in high yielding corn. Overall, NRE was quite low in this trial. However, keeping soil conditions at or near field capacity during periods of high N uptake will likely improve NRE.

1.3 Right Source Overview

In Indiana and most Midwest states, anhydrous ammonia, urea, and UAN make up the bulk of the N fertilizer sources used in corn production. Tri-State Fertilizer Recommendations (Vitosh et al., 1995) for Indiana, Ohio, and Michigan recommend anhydrous ammonia (82% N) be injected well below the soil surface. One advantage for anhydrous is that it is the slowest of the three sources to convert to nitrate (NO_3^-) N (Brady and Weil, 2009). Urea ammonium nitrate (UAN: 28-32% N) can be subsurface or surface band applied and is partially subject to leaching and denitrification immediately after application. Urea (46% N) is typically broadcast on the surface and associated N volatization losses can be high especially when the weather is dry and urea is applied to fields with high residue cover.

All N sources are subject to loss whether that be from urea hydrolysis, ammonia volatilization, gaseous losses of N_2 and/or N_2O, or nitrate leaching. Common N sources like anhydrous ammonia, urea, and UAN undergo urea hydrolysis at some point immediately after or shortly following application. Urea hydrolysis removes hydrogen (H^+) ions resulting in a temporary decrease in the soil pH near the fertilizer source (Jones et al., 2007). Additionally, ammonia gas from fertilizer sources can be converted to NH_3 and lost to the environment through ammonia volatilization (Brady and Weil, 2009). While each N source varies in potential loss experienced through various mechanisms, N source has been known to alter plant performance. For example, Jung et al. (1972) found grain yield, tissue yield, grain N, stover N, and total N uptake improved using urea and ammonium nitrate (NH_4NO_3) sources over potassium nitrate (KNO_3) applied at similar N rates. Factors like placement, rate, potential loss, and cost can influence which source is most appropriate.

1.4 Right Rate Overview

Proper N rate for soil conditions at the time of application can reduce ammonia (NH_3) and ammonium (NH_4^+) toxicity concerns. Gaseous fertilizer bands can result in NH_3 toxicity; toxicity has been documented in corn when seedlings are continuously exposed at low vapor concentrations for long periods, or at high concentrations for short periods (Goyal and Huffaker, 1984). Symptoms of ammonia and ammonium toxicity for plants include root damage, stand loss, chlorosis of leaves, suppression in growth, reduced yield, and possibly a reduction in root-to-shoot ratios (Goyal and Huffaker, 1984; Britto and Kronzucker, 2002; Pan et al., 2016).

1.4.1 Pre-Plant N Rates

Pre-plant (spring) N applications offer corn growers an effective and safe method of supplying a partial or full season N rate while in-season applications can be conflicted with high rainfall that prohibit further applications (Vitosh et al., 1995). In Indiana corn production, economic optimum N rates (EONR) ranged from 190 to 235 kg N ha^{-1} depending on fertilizer cost, grain price, and geography (Camberato and Nielsen, 2019). A study by Omonode et al. (2015) utilized pre-plant applications (145 and 202 kg N ha^{-1}) and found that the 145 kg N ha^{-1} rate (30% lower rate than agronomic optimum) reduced N_2O emissions 65% without a significant decrease in yield. However, when N is applied entirely at pre-plant timings, Bjorneberg et al. (1998) found a greater likelihood for denitrification and leaching losses to occur.

1.4.2 At-Plant N Rates

Farming practices that utilize high rates in pre-plant and at-plant systems are more common than planter applied N as most modern planters cannot achieve delivery of even 50% of a full N rate at efficient planting speeds. Small quantities of planter applied N are typically in the form of “starter fertilizer”; a placement of fertilizer that is near the seed (typically a combination of N-P_2O_5-K_2O-Micronutrient(s)). Starter fertilizer is most commonly applied at 5cm by 5cm (5x5) distance from the seed or in-furrow (Camberato et al., 2016). Starter fertilizer rates typically do not exceed 20-40 kg N ha^{-1} at the 5x5 location (Ciampitti et al., 2013). In one exception, a planter-applied banded N study with low to moderate rates ranging from 34 to 134 kg N ha^{-1} found that increasing starter fertilizer >34 kg N ha^{-1} did not result in corn plant growth or yield benefits when followed by a broadcast N application shortly after planting balancing all treatments to 168 kg N ha^{-1} (Niehues et al., 2004). Contrary to Niehues, Becks Hybrids practical farm research (PFR) found corn yield improvements as at-plant N rates increased from 34 to 67 kg N ha^{-1} across multiple locations, including Indiana (Beck's Hybrids, 2018, not supported by statistical analysis).

The development of real-time kinematic (RTK) technology allows precise N bands to be positioned parallel to the intended corn rows just before planting. Vyn and West (2009) studied high N rates at various placements from the seed row. In their research, UAN was banded by coulter injection at 7 to 8cm deep in a separate RTK-guided pass within a day before RTK-guided planting. Among three locations, corn yield was reduced as at-plant N rate increased from 56, 112, and 224 kg N ha^{-1} and as the N band moved progressively closer to the seed (from 25cm, 13cm, and on-row). On-row placements at 224 kg N ha^{-1} reduced plant stand by 13,000 plants ha^{-1} on sandy loam soils compared to when N was placed off-row (Vyn and West, 2009). High N rates were successful in maintaining yields with off-row placements at some locations. Vyn and West confirm that high at-plant N rates banded near seeding can be utilized effectively if soil conditions and N placement do not alter seedling emergence or early growth and development.

1.4.3 Sidedress N Rates

Sidedress applications (usually before V7) involving high N rates typically follow starter fertilizer or at-plant N applications of low N rates. A 49 site-year study by Kitchen et al. (2017) found a decrease in the economic optimum N rate (EONR), increased yield at the EONR, and increased agronomic efficiency of N when split N (using ammonium nitrate as the N source) of 45 kg N ha^{-1} was broadcast applied at planting and the remainder broadcast at V9 versus a single at-plant N application (45-270 kg N ha^{-1} in 45 kg N ha^{-1} increments in development of the EONR model). Studies featuring a split N application approach between pre-plant/at-plant and early sidedress (Killorn and Zourarakis, 1992; Schröder, 1999; Abbasi et al., 2012), late sidedress (Mueller et al., 2017), or multiple sidedress applications (Gehl et al., 2005), typically find little to no consistent yield advantage even across multiple total N rates. Physiological maturity N and NRE were improved, but not grain yields, with late sidedress applications of 45 kg N ha^{-1} at moderate total N rates (200 kg N ha^{-1}) when early drought stress limited N uptake (Mueller et al., 2017). In comparison, a more typical sidedress distribution of 185 kg N ha^{-1} split between at-plant (1/3 of total N rate) and V6 sidedress (2/3 of total N rate) produced similar yields when compared to higher N rates between 250 and 300 kg N ha^{-1} applied in a single at-plant application or 250 kg N ha^{-1} split evenly between at-plant and V6 sidedress (Gehl et al., 2005).

1.5 Right Time Overview

Major N application timings are typically fall, spring (pre-plant or at-plant), or in-season sidedress. The timing of nutrient applications can be critical in optimizing yield, unfortunately, there is not a "silver bullet" for N timing. For example, Kovács et al. (2015) studied NH_3 applications before planting and at sidedress and found corn yields greatest with a pre-plant application timing in one site year and a split application yielding greatest another year. Conflicting data within and among timing studies has led to continued sidedress research. Previous research has documented that pre-plant and sidedress applications tend to be superior over fall N applications (Welch et al., 1971; Randall et al., 2003; Randall and Vetsch, 2005), likely due to decreasing the potential for leaching and maximizing a plant's potential uptake. Early work by Jung et al. (1972) found yield and biomass decreased if N was delayed past 8 weeks from planting while stover and grain N concentrations improved with post 8 week N applications.

1.5.1 Pre-Plant and At-Plant N Timing

Pre-plant N timings generally refer to the timeframe 1 to 2 weeks before planting while at-plant refers to the ±48 hours from planting. Both methods follow similar trends of inconsistencies in yield benefits compared to alternate timings. Farmers that apply most or all N pre-plant typically choose NH_3 as their source as it is the most cost-effective per unit N. However, depending on soil moisture at and after application, NH_3 needs to remain in the soil for 1 to 2 weeks before planting for N toxicity concerns to subside (Colliver and Welch, 1970). One incentive with fall N application is that it does not overlap with planting and tillage operations like pre-plant applications. However, Randall and Vetsch (2005), showed a 0.51 Mg ha^{-1} yield advantage for pre-plant versus fall applications in 3/6 site years. Occasionally, plant performance is improved with a single pre-plant application over sidedress. This has been confirmed in previous research by Russelle et al. (1981) who found an increase in corn N uptake with pre-plant applications over sidedress. Concurring with Russelle, Kovács et al. (2015) found at a total N rate of 202 kg ha^{-1} that plant N uptake and grain yield were improved when N was supplied entirely at pre-plant versus a V6-V7 sidedress application.

1.5.2 Sidedress N Timing

Sidedress N applications tend to occur between V4 to V6 (early), modern high-clearance equipment technology allows for applications at V10 to V14 (late), and even at or after R1 (silking). Early sidedress N timings have proven superior to pre-plant in grain yield (Miller et al., 1975; Olson et al., 1986; Randall et al., 2003; Gehl et al., 2005; Abbasi et al., 2013; Wells et al., 2013; Kovács et al., 2015), total N uptake (Jokela and Randall, 1997; Burzaco et al., 2014; Sainz Rozas et al., 2004; Abbasi et al., 2012; Abbasi et al., 2013), and NRE (Randall et al., 2003; Abbasi et al., 2012; Abbasi et al., 2013; Ciampitti and Vyn, 2013; Burzaco et al., 2014). However, in other trials, sidedress timing results in equal grain yields (Welch et al., 1971; Killorn and Zourarakis, 1992; Jokela and Randall, 1997; Randall et al., 2003; Randall and Schmitt, 2004; Jaynes, 2013) or even reduced grain yields (Jung et al., 1972; Jaynes and Colvin, 2006), as well as not improved N uptake (Jung et al., 1972; Killorn and Zourarakis, 1992; Jokela and Randall, 1997; Randall et al., 2003) or NRE (Randall and Schmitt, 2004). A recent review including 14 sources by Fernandez et al. (2019) found no difference among early and late sidedress timings. Improved grain yield, N uptake, and NRE were achieved by pre-plant NH_3 applications versus V6 to V7 sidedress applications (Kovács et al., 2015). Scharf et al. (2002) concluded there was never an instance when a single N application at V11 decreased yield, rare instances of small reductions at V12 to 16 (<3%), and minor to moderate reductions at R1 (<15%) compared to a single at-plant application.

Sidedress applications do not always result in a direct yield or N uptake advantage, sidedress provides more flexibility for growers to reduce or increase total N rates in response to early growing season factors. Researchers have confirmed that the total N rate could be reduced by as much as 10 to 15% with sidedress N application versus an at-plant or pre-plant N application, (Brouder et al., 2003; Venterea et al., 2016). Even at the R1 stage, late sidedress N (occasionally termed “rescue applications”) can increase grain yield in N stressed plants (Binder et al., 2000; Jaynes and Colvin, 2006; Mueller and Vyn, 2018). Nevertheless, there are limits to the efficacy of such late applications; Mueller and Vyn (2018) found plants could only fully recover final yields when vegetative stage biomass accumulation and early season plant health was not compromised by N deficits before flowering. Therefore, sufficient early N must be accessible to not compromise leaf expansion during vegetative growth and development (Mueller and Vyn, 2018; Rutan and Steinke, 2018) for R1 stage N applications to be effective.

Split N applications and topdressing wheat have been extensively researched to increase protein quality and improve grain yield. Research focused on in-season soil-applied N with common wheat varieties by Blandino et al. (2015), found improved grain protein content, test weight, kernel hardness, and dough strength. However, a late-season N application did not increase yield, kernel weight, or test weight (Blandino et al., 2015). Split applied N was unable to produce winter wheat of the same yield and quality as spring-applied N unless a majority of the split applied N was applied in the spring with a smaller amount being applied later in the growing season (Vaughan et al., 1990). In sandy soils, splitting N increased wheat grain yields in one of two site years, while N uptake was increased in both years (Gravelle et al., 2013). Research conducted in wheat with split sidedress applications concluded similar inconsistencies to that of corn.

Genetic advancements in corn hybrids have led to greater post-silking N uptake and increased ability for plants to recover N. Current practices of late-season N applications are trying to further capitalize on the higher potential N uptake as well as an extended period of peak N uptake in modern hybrids. Management strategies that capitalize on these genetic and technological advancements could potentially minimize environmental loss and optimize the plant's ability to recover fertilizer N. Mueller and Vyn (2016) found new hybrids (post-1991) recovered a greater proportion of their total N uptake in the post silking period than older hybrids (pre-1991). Ciampitti and Vyn (2012) found new hybrids (post-1991) had a greater total N uptake at R6; these findings led researchers to believe that new hybrids will routinely recover more post silking N, thus increasing N uptake and NRE relative to older hybrids. However, late split N (55 kg N ha^{-1} at R1 following a V4 sidedress application of 165 kg N ha^{-1}) was not beneficial to total plant N uptake, NRE, and grain yield relative to a single 202 kg N ha^{-1} application at the V4 stage in a recent Pioneer era hybrid study (Mueller and Vyn, 2018).

1.6 Right Placement Overview

Fertilizer placement trials have been extensively researched and, much like timing, data gathered from placement trials are typically inconclusive with negative, neutral, and positive responses. Nitrogen can be applied in many ways; most commonly N is applied broadcast or banded (subsurface or surface) while very low rates can be applied in-furrow at planting.

Placement can be a critical factor in maximizing yield by minimizing nutrient loss, avoiding toxicity issues, and increasing plant nutrient uptake. Fox et al. (1986) showed ammonium nitrate (surface banded or injected) and injected urea produced similar corn yields and plant N uptakes when averaged across at-plant and sidedress timings. When N is placed below the soil surface researchers have found a reduction in gaseous N loss (Drury et al., 2017) and improvements in grain yield (Mengel et al., 1974). However, other studies have shown no impact on grain yield from subsurface versus surface placements (Maddux et al., 1991). Although Maddux et al. (1991) did not show a grain yield advantage, their subsurface placement led to improved N uptake. In agreement with previous work in corn, Mazdid Miah et al. (2016) found deep placement decreased fertilizer need by 30-45% versus a surface broadcast application in rice production. Conclusions from these researchers tend to favor subsurface placements as offering a more reliable placement for N fertilizer applications.

1.6.1 At-Plant and Planter Applied N Placement

At-plant N sources are commonly subsurface banded or surface broadcast at partial to full-season N rates. In contrast, planter applied N is most commonly placed at the 5x5 location, occasionally in-furrow, and more recently at the 5x5x5 location at starter fertilizer rates. The 5x5x5 placement is similar to the 5x5 placement except fertilizer is placed on each side of the row instead of on a single side, which distributes fertilizer more evenly. Becks Hybrids practical farm research (Beck’s Hybrids, 2018) compared 5x5 and 5x5x5 with claims of slightly improved yield when utilizing the 5x5x5 placement of a 18-18-0 fertilizer at 140.3 L ha^{-1} (not supported by statistical analysis). Comparing on row versus 5x5 placements of a blended N source (ammonium nitrate, ammonium sulfate, monoammonium phosphate, and ammonium thio-sulfate at 22.4 kg N ha^{-1} (22.4, 9.8, and 22.2 kg ha^{-1} of N, phosphorus, and sulfur, respectively), researchers did not find consistent differences in a no-till system (Wortmann et al., 2006). Niehues et al. (2004) found similar results from fertilizer placed on the seed, dribbled over the row, and at the 5x5 location with low N rates (11-56 kg N ha^{-1}) of ammonium nitrate.

Previously mentioned work by Vyn and West (2009) utilizing multiple at-plant N rates (56, 112, or 224 kg N ha^{-1}) and placements (on-row, 13cm, or 25cm distances from the seed row) with a UAN source found placement greatly influencing the success of N rates. Stand reductions were observed at two of three locations with on-row placements compared to the 13cm and 25cm wide placements. A stand reduction of ~7,000 and ~13,000 plants ha^{-1} was observed at two of the three locations at the highest N rate. The 112 kg N ha^{-1} rate did not result in stand loss at one location with a ~3,400 and ~5,700 plants ha^{-1} stand loss at the other two locations. On-row placements of the 56 kg N ha^{-1} rate showed no loss at two locations and only a minor loss of ~2,000 ha^{-1} plants at the third. Evident from this work, N placement can alter the final plant stand associated with N toxicity at moderate to high N rates coinciding with planting operations.

Research comparing emergence timed applications of three urea sources (urea, polymer-coated urea, and stabilized urea) at 202 kg N ha^{-1} between surface banding and broadcast methods found no treatment differences in corn grain yield or N uptake (Halvorson and Grosso, 2013). While placement was not influential for Halvorson and Grosso (2013), Maddux et al. (1991) found N recovery to be greater from banded UAN than from the same rate of broadcast urea.

1.6.2 Sidedress N Placement

At a traditional sidedress timing between V4 to V8, it is common for N to be mid-row subsurface injected with broadcast and surface banding applications offering greater flexibility in placement options. Surface banding can vary in placement from a single band to multiple bands. A popular multiband surface application method is the Y-Drop™ system. Y-Drop™ was created by Yield 360 (Morton, IL) and delivers liquid N to each side of the corn plant at the base of the stem, similar to the 5x5x5 planter-placement concept but on the soil surface. In Michigan, Steinke and Purucker (2018) found coulter injection of UAN performing better than Y-Drop™ in a single year trial at one location with a neutral response at their second location under conventional tillage and averaged across timings (50:50 split pre-plant incorporated and V6 sidedress, 100% V6 sidedress, and 45 kg N ha^{-1} 5x5 banded and remainder V6 sidedress) and rates (163 and 191 kg N ha^{-1}). Woodley et al. (2018) concluded similar results as Steinke under conventional tillage in Ontario, Canada finding a yield advantage for sidedress injected UAN as surface streaming lowered N uptake and increased volatilization losses when >50% of the ~158 kg N ha^{-1} was supplied at sidedress. In an earlier comparison of injected NH_3 versus incorporated dribbled UAN, injection resulted in the greatest yield (Randall and Schmitt, 2004).

1.7 Overall Weather Impacts

Water availability and uptake directly relate to a plant's ability to recover nutrients and timely and adequate rainfall ensures surface-applied nutrients are incorporated reducing volatilization. When drought stress occurs during vegetative growth, either simulated through irrigation or natural, at-plant and pre-plant applications generally perform better than split applications in corn (Jokela and Randall, 1989; Bjorneberg et al., 1998; Randall et al., 2003; Randall and Schmitt, 2004; Gehl et al., 2005; Maharjan et al., 2016; Steinke and Purucker, 2018) and wheat (Vaughan et al., 1990). In contrast, pre-plant or at-plant applications can be detrimental when high N leaching or denitrification losses occur with excessive rainfall that keeps soil above field capacity during early vegetative growth.

Volatilization is the primary mechanism for loss from surface-applied fertilizer; Fox et al. (1986) showed N volatilization positively correlated to the number of days from application until 10mm of precipitation was recorded. Volatilization was near zero when 10mm of precipitation was recorded within 2 days, was minimal if within 3 days, and found progressively increasing loss as dry conditions prevailed (Fox and Hoffman, 1981; Fox et al., 1986). During a high rainfall growing season, researchers found a V10 sidedress application of urea increased grain yield compared to a pre-plant control of the same total N rate (Kaur et al., 2017). The same study also concluded that a V10 N application was only effective if there was adequate rainfall following application (Kaur et al., 2017).

1.8 Overview of Research Gaps in 4R Nutrient Management for Corn

The four R's of nutrient stewardship directs growers to use the right source, rate, time, and placement of fertilizer to meet their operational needs and yield goals. Many publications provide insight into opportunities for an individual R adjustment for improved corn yield performance in specific environments. Prediction of the most effective combination of 4R strategies from that past research is constrained by the scope of such research. Furthermore, the "right" source, rate, time, and place that best meets both crop needs and grower requirements is often not known with certainty before or even during the growing season. Many tools have been developed to assist in N rate recommendations, but extreme difficulty in predicting the EONR makes improved yields or profits elusive (Ransom et al., 2019). Researchers and crop consultants typically have more certainty about "best management practices" post-harvest, but there is still much to be learned from new and ongoing research with replicated N treatments (utilizing common N sources) that study possible interactions between rate, timing, and/or placement that may enhance both crop and environmental outcomes. The study of potential 4R strategy interactions becomes even more relevant when planter and N applicator equipment capability advances, and as corn hybrids and other corn management systems change.

Nitrogen rate has received the most research attention to develop models and optimum N rate strategies for various geographies and soil types. When conducting sidedress research and significant differences were observed, it is generally reported that subsurface placements are advantageous relative to surface N applications. However, differential N placements have often been reported to result in similar corn yields. Because most of the past N placement research has not involved the use of intentionally high N rates at planting, or the use of Y-Drop™ technologies with multiple sidedress timings, further research is warranted.

Planter applied N has not been researched to determine the effectiveness of applying ≥50% of the total N rate for high yielding corn cropping systems. Being able to apply a 50 to 100% of a total N rate while planting allows growers to become more efficient by eliminating a pass across the field and possibly increasing plant growth, development, and/or yield.

Sidedress N has occasionally proven to be more effective than pre-plant applications for corn yields and whole-plant N recovery, but weather and growing conditions, as well as interactions with N rate, can confuse the outcomes that are realized. The literature confirms that sidedress N rate typically should not exceed >50% of the total N rate, especially when N is delayed into the late vegetative or early reproductive growth stages (Mueller and Vyn, 2018).

Sidedressing corn at either early or late timings offers growers the potential for greater yields when weather and crop growing conditions promote early season N loss. Growing season weather is crucially important to crop growth and health, with precipitation timing and amount following N applications strongly influencing treatment outcomes. Managing N timing with the precipitation forecast is possibly more important than N timing itself with surface-applied nutrients like N.

Managing N in a corn cropping system is highly complex and results of specific 4R nutrient management strategies can vary from year to year. It is highly unlikely a single "best management practice" for N will be concluded, but continued research with modern technologies will offer growers more information to apply to their soils and specific management systems.

1.9 Research Objectives

The primary research objective was to determine the implications of relatively new N management on corn growth, yield responses, and in NRE or other N efficiencies within rainfed environments in Indiana.

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CHAPTER 2. THE INFLUENCE OF PLANTER APPLIED NITROGEN AT VARIOUS RATES AND PLACEMENTS ON CORN GROWTH, DEVELOPMENT, AND GRAIN YIELD

2.1 Abstract

Planter applied nitrogen (N) in corn (*Zea mays* L.) strategies have remained relatively unchanged for several decades with relatively low starter fertilizer rates applied (typically <10-20% of the growing season total N applied). A two-year (2017 and 2018) field trial involving continuous corn was conducted near West Lafayette, Indiana to investigate the effects of planter-applied N at various band placements from 5cm x 5cm (5x5) (distance from soil surface x distance from seed row) to 10cm x 20cm (10x20) at planter applied rates of 34, 101, or 202 kg N ha^{-1} followed by a mid-row sidedress application near V5 to V6 (if required) to achieve a uniform total N rate of 202 kg N ha^{-1}. Because all placement by N rate treatment combinations were not balanced, our analysis and results focused on the 5x5 and 10x5 placements at all three N rates. In 2017, differential yield responses were not found for N placement (between 5x5 and 10x5) or N rate (among 34, 101, and 202 kg N ha^{-1}). In 2018, the 5x5 placement (averaged across 34, 101 and 202 kg N ha^{-1} rates) improved grain yield 6.6% relative to the 10x5 band placement. In both years, harvest moisture was reduced by banding 101 versus 34 kg N ha^{-1} while 202 kg N ha^{-1} was not different among planter applied rates. In 2018, planter banding of 101 kg N ha^{-1} resulted in a consistent advantage across placements (5x5 and 10x5), relative to 34 kg N ha^{-1}, in grain yield, kernel number $plant^{-1}$, harvest moisture, plant biomass accumulation, plant N uptake, N use efficiency (NUE), and N recovery efficiency (NRE) for the primary analyses. An alternative statistical analysis including 6 placements (5x5, 5x13, 5x20, 10x5, 10x13, and 10x20) at the 101 and 202 kg N ha^{-1} rates also found no placement consequences for yield in 2017. However, the 5x13 and 10x20 banding (averaged across 101 and 202 kg N ha^{-1} rates) treatments in 2018 reduced yield by 12.5% and 10.5%, respectively, when compared to 5x5 banding. This alternative analysis found banding of N at either 13 or 20cm distances occasionally reduced yield via a kernel number reduction. In summary, at-plant N should be placed near the seed row (i.e. 5x5 or 10x5) and banded at moderate rates (i.e. 101 kg N ha^{-1}) for maximum N efficiency and grain yield in similar soil situations when corn follows corn.

2.2 Introduction

A continuing need to optimize farming practices has been challenging farmers and crop consultants for decades as they must adapt to changing climates, markets, and political environments. One way to confront these challenges is to become more knowledgeable about agronomic practices currently employed, or develop new strategies that are more efficient and profitable. Nitrogen (N) fertilizer use in modern agriculture is under increased scrutiny from societal concerns for associated water and atmospheric pollution. However, the importance of N in modern agriculture should not be overlooked. Nitrogen is often the most limiting variable behind water, reducing both crop growth and yield when soil mineral N availability is insufficient for crop demand. Improving the use of N in production agriculture could prove vital in global food security and sustainable agriculture (Gaffney et al., 2019). To truly appreciate the implications of N management on N recovery efficiency (NRE) and yield, it is important to recognize the current understandings of N timing, rate, placement, and source.

In-season N applications have been favored by farmers trying to capitalize on targeted N applications with improved synchrony to peak corn N uptake around the V10 stage (Bender et al., 2013) while reducing environmental losses to leaching and volatilization. Some researchers have focused on in-season applications of dry granular N products and their potential yield benefits compared to pre-plant and at-plant applications. Comparing at-plant and early (~V5) sidedress, Wells et al. (2013) found an increase in flowering (R1) earleaf N% and grain yield with sidedress applications of broadcast urea and ammonium nitrate sources averaged across two total N rates (90 and 180 kg N ha^{-1}) in Kentucky. Gehl et al. (2005) always observed equal yields between 185 kg N ha^{-1} split applied at-planting (33%) and V6 to V8 sidedress (66%) versus single at-plant applications of 250 or 300 kg N ha^{-1} in a 10-site year study utilizing granular ammonium nitrate on a sandy irrigated loam in Kansas. In a 49-site year study covering much of the U.S. Corn Belt (Kitchen et al., 2017) that compared various N rates of broadcast ammonium nitrate applied at-plant versus split sidedress applications, split N timings lowered the economic optimum N rate (EONR), increased grain yield at EONR, and increased N use efficiency (NUE). In contrast, Nasielski et al. (2020) found a neutral response to N timing on grain yield at the EONR among four N timings (100% AP, 100% at V6, 50:50 split between AP and V6, or 50:50 split between V6 and V13) despite a slight reduction in volatilization loss with in-season applications averaged across source (urea and UAN) and placement (surface broadcast and incorporated) in Canada.

Corn yield was not influenced in Brazil among N timings (pre-plant, at-plant, or V3 toV6 sidedress) of urea at rates between 150-180 kg N ha^{-1} in a labeled N^{15} experiment even though NRE improved with V3 to V6 applications over pre- and at-plant applications (Maciel de Oliveira et al., 2018). While these previously mentioned studies all favor sidedress or split N applications to achieve higher NUE, NRE or yield, a study in Minnesota (Jokela and Randall, 1989) observed a site-dependent response for N uptake, NRE, and grain yield in comparisons of at-plant, V8 sidedress, or split-N treatments with ammonium sulfate at various rates from 75-300 kg N ha^{-1}. Scharf et al. (2002) modeled relative yield as a function of timing from 28 separate N timing experiments in Missouri where a single N rate of 180 or 225 kg N ha^{-1} was applied and found no yield loss if N was applied prior to V11, minor reductions (<3%) between V12-V16, and moderate reductions (<15%) when N was entirely delayed until flowering (R1).

Nitrogen sources like liquid UAN or anhydrous ammonia (NH_3) have not been used as often in small-plot research as dry N sources despite their more common use in Midwest corn production. Several literature reports on timing effectiveness tend to disagree with the previously mentioned studies featuring dry N sources. Jaynes and Colvin (2006) found a single postemergence broadcast application of UAN at 138 kg N ha^{-1} yielded 0.80 and 1.61 Mg ha^{-1} more in 2002 and 2004, respectively, when compared to an evenly split N application between emergence and V16 in Iowa. Like Jaynes and Colvin, Kovács et al. (2015) found pre-plant applications of NH_3 improved corn yields over a V6 to V7 sidedress application on a silty clay loam soil in Indiana.

While pre-plant and at-plant N applications occasionally improve yield relative to sidedress applications at the same N rates, potential denitrification and leaching loss is more likely with pre-plant and at-plant applications (Bjorneberg et al., 1998). It is clear from the available research on differing N sources that the yield and/or N recovery response effectiveness of specific N application timings is still variable. These conflicting results continue to make recommendations for individual N source and desired N application timing difficult.

Water availability plays an integral part in N availability and plant N uptake; thus, soil moisture and precipitation are important factors in determining if N timing differences occur. Research conducted on irrigated sandy loam soils in Minnesota comparing surface broadcast urea at 8 rates (45-315 kg N ha^{-1}) found split N applications increased grain yield and NRE when compared to single at-plant N applications with a neutral response in a dryland environment

(Maharjan et al., 2016). The timing of precipitation is also important; a review by Morris et al. (2018) stated that receiving rain soon after N application was highly influential in determining treatment separation with NRE. In planter-applied N systems, both adequate soil moisture and precipitation following application may be necessary to prevent N toxicity from damaging seedlings. This has been confirmed by Colliver and Welch (1970), who noted that in NH_3 applications, a wait period before seeding was necessary for N toxicity concerns to subside; when adequate soil moisture is present, the time between N application and seeding can be reduced.

At-plant and planter-applied N applications are challenged with increased ammonia toxicity concerns as N rates progressively increase and proximity to corn seeds and seedling roots decreases. Because of this, most at-plant N applications are broadcast applied and little research exists for banded UAN at-planting. Well-distributed N limits toxicity concerns even if high N rates are employed. When at-plant banded N is studied, rates rarely exceed 50% of the total N rate to avoid ammonia toxicity complications. Seedling toxicity has been documented when corn seedlings are continuously exposed to low ammonia vapor concentrations for long periods or at high concentrations for short periods (Goyal and Huffaker, 1984). Nitrogen toxicity can inhibit young growing plants leading to reduced yields and possibly a reduction in root-to-shoot ratios (Goyal and Huffaker, 1984; Britto and Kronzucker, 2002). Research in wheat by Pan et al. (2016) found wheat seminal roots mostly avoiding both banded UAN and polymer-coated urea at low to moderate N rates; however, when urea was placed with the seed at 56 or 112 kg N ha^{-1} all roots perished.

The concept of applying fertilizer with a planter is not new. Starter fertilizer has been utilized in corn cropping systems for decades and has been proven effective (Bermudez and Mallarino, 2002). However, N rates in starter fertilizer bands typically do not exceed 20% of the intended total N rate. Niehues et al. (2004) exceeded 20% starter fertilizer rates in a Kansas based field trial while investigating rates from 34-134 kg N ha^{-1} (20 to 80% of the total 168 kg N ha^{-1} rate) with UAN banded at 5cm x 5cm (from seed placement) in a continuous corn no-till cropping system. These researchers found rates ≥34 kg N ha^{-1} did not further improve plant growth or yield. Little published research has been conducted in planter-applied N at rates exceeding 20% of the total N rate, perhaps due to a combination of factors including a lack in equipment technology, funding, and concerns with ammonia toxicity to young seedlings.

Placement of N can be just as important as timing or rate in managing N efficiently and effectively. Research utilizing a formulated UAN solution found no yield impact when placed on the seed, dribbled over the row, or at the 5cm x 5cm (from seed placement) location with 34 kg N ha^{-1} rates in continuous no-till corn (Niehues et al., 2004). At higher at-plant N rates comparing surface banding (within 10cm of the seed row) and broadcast of three sources (urea, polymer-coated urea, and stabilized urea) at 202 kg N ha^{-1}, researchers found no differences in grain yield or N uptake on an irrigated clay loam in Colorado (Halvorson and Grosso, 2013). While these studies demonstrated no placement advantages, a labeled N_{15} study found improved NRE from banded (15cm by 5cm, depth by distance from seeding) UAN at 168 kg N ha^{-1} over broadcast incorporated (2 to 3cm) UAN with a separate application just prior to planting on a silt loam in Kansas (Maddux et al., 1991). Like Maddux, Szulc et al. (2020) found an increase in corn yield with subsurface banded N over broadcast applications at 100 kg N ha^{-1} while N source (ammonium nitrate or urea) did not influence results from research conducted in Poland.

At-plant N can potentially reduce plant stands influencing yield when N is applied at too high of a rate or placed too close to seeds at the bottom of the seed furrow. Vyn and West (2009), conducted research at three Indiana locations varying in surface soil texture (clay loam, silt loam, and sandy loam soils) and observed a stand reduction of 7,000 and 13,000 plants ha^{-1} on clay and sandy loams, respectively, when utilizing on-row UAN placements at 224 kg N ha^{-1} compared to UAN bands offset 13cm and 25cm from the seed row. At lower rates of 112 kg N ha^{-1} and 56 kg N ha^{-1}, stand reductions were still evident when N was applied on-row, but not when placed either 13 or 25cm from the row. While at-plant N can influence yield if toxicity issues inhibit stand or stunt early plant growth, the varying genetic, management, and environmental conditions in addition to N rate, source, and placement influences we have described make broad conclusions difficult.

Planter technology advancements have typically focused on seed singulation and increased planting speeds to improve plant stand and vigor while also making planting more efficient. Less emphasis has been placed on improving nutrient delivery strategies with planting systems. In this experiment, we studied various planter applied N rates in a continuous corn cropping system at lower than agronomic optimum N rates where N related stress would be prevalent. We hypothesized that safe and yield-effective planter applied fertilizer placements will be different from the commonly employed 5cm x 5cm (from seed placement) starter fertilizer placement. We also hypothesized that 202 kg N ha^{-1} rates banded at planting would have a negative influence on yield as N loss and potential seedling toxicity would reduce plant stands and inhibit early-season growth. Our specific objectives of the study were to (i) monitor and assess any negative growth or stand reductions that could occur from the various N rate and placements implemented (ii) determine if planter N placement and or rate influenced plant growth rates, biomass accumulation, and/or grain yield, and (iii) investigate if alternative placements and non-typical rates could be safely utilized by modern planters to improve both N application efficiency and plant responses in a conventional tillage continuous corn cropping system.

2.3 Materials and Methods

A two-year (2017 and 2018) field-scale experiment was conducted near West Lafayette, Indiana at Purdue University's Agronomic Center for Research and Education (ACRE) farm (40.489°N, 87.008°W). The trial was conducted in the same field with re-randomization of plots in the second year. The site consisted primarily of a 0-2% sloping, Drummer silty clay loam (Fine-silty, mixed, superactive, mesic Typic Endoaquolls) and a 0-1% sloping, Raub-Brenton complex silt loam (Fine-silty, mixed, superactive, mesic Aquic Argiudolls) soil. Average fertility derived from 10-12 cores taken to 20cm for both years (2017, 2018) for soil pH, organic matter (OM), and cation exchange capacity (CEC) were 6.1 (6.1, 6.1), 3.4% (3.3, 3.5), and 20.4 cmol$_c$ kg^{-1} (19.7, 21.0), respectively. Soil phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentrations were 19.3 mg kg^{-1} (16.0, 22.5), 157 mg kg^{-1} (130, 204), 2,294 mg Ca^{-1} (2,164, 2,424), and 610 mg Mg^{-1} (587, 633), respectively. Analyses were conducted at A&L Laboratories (Fort Wayne, IN) using the recommended chemical soil test procedures for the North Central region (Denning et al., 2011).

A total of 17 treatments were investigated in 2017, and the same 17 (re-randomized in 2018) plus the addition of 2 zero N treatments/replication were investigated in 2018 in a randomized complete block design. Because of funding and practical operational constraints, three treatments were only featured at a single placement and/or rate (i.e. not allowing for mean comparisons across multiple placements and rates) and thus only 14 treatments were included in this analysis (Table 2.1). Planter-applied N supplied by urea ammonium nitrate (UAN) was banded at rates of 34, 101, or 202 kg N ha^{-1} at placements (distance from the soil surface x distance from the seed row) of 5cm x 5cm (5x5), 5cm x 13cm (5x13), 5cm x 20cm (5x20), 10cm x 5cm (10x5), 10cm x 13cm

(10x13), or 10cm x 20cm (10x20) (Table 2.1). Alternative N placement were accomplished with an experimental John Deere prototype DB20 (John Deere, Moline, IL) that was fitted with a liquid N coulter delivery system mounted separately from the seed row. The coulter unit could slide between 5 and 20cm distances from the seed row in 1.25cm increments. Each 101 and 202 kg N ha^{-1} planter applied N rate was represented at all placements included in this analysis while the complete combination of 34, 101, and 202 kg N ha^{-1} planter applied N rates were only present at the 5x5 and 10x5 placements (Table 2.1).

Table 2.1. Planter applied N treatments used in both 2017 and 2018. Nitrogen timings consist of at-plant (AP) and sidedress (SD) at a common 202 kg N ha^{-1} total N rate for all treatments.

AP N Placement†		Application Timing		
Depth	Distance	AP	SD	Total
(cm)		(kg N ha^{-1})		
5	5	34	168	202
5	5	101	101	202
5	5	202	0	202
5	20	101	101	202
5	20	202	0	202
5	13	101	101	202
5	13	202	0	202
10	5	34	168	202
10	5	101	101	202
10	5	202	0	202
10	13	101	101	202
10	13	202	0	202
10	20	101	101	202
10	20	202	0	202

†At-plant N was planter banded at 5 or 10cm depths (from the soil surface) and at 5, 13, or 20cm distances (from the seed row)

The experiment was conducted in a continuous corn conventional tillage cropping system. Fall deep ripping and secondary spring cultivation were used to manage previous crop residue and prepare the seedbed. The 8-row plots with 0.76m row spacing at ~67m in length were planted with a John Deere ExactEmerge™ planter (John Deere, Moline, IL) at 6.5-8.0 km h^{-1} on 24 May 2017 and 12 May 2018. The same hybrid, P1417AMX (Corteva Agriscience, Wilmington, DE), was seeded each year at 81,500 seeds ha^{-1} and final mean populations averaged 82,000 and 76,700 plants ha^{-1} in 2017 and 2018, respectively. At the V5 to V6 stage (Abendroth et al., 2011), a mid-row banded UAN sidedress application supplied 101 and 168 kg N ha^{-1} to the 101 and 34 kg N ha^{-1} planter applied rate treatments, respectively, thereby balancing all treatments besides the zero N control to a common 202 kg N ha^{-1} total N rate on 22 June 2017 and 5 June 2018. Post-emergence herbicide applications were made to control weeds shortly after planting with glyphosate [*N*-(phosphonomethyl)glycine] (Bayer CropScience, St. Louis, MO) at 1,400 g ha^{-1} and Bicep {metolachlor-[2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1methylethyl) acetamide]/atrazine[6-chloro-N-ethyl-N-(1-methylethyl)-1,3,5-triazine-2,4-diamine]} (Syngenta Agrochemical Company, Basel, Switzerland) at 5.6 L ha^{-1}. In-season weed control utilized glyphosate at 1,400-2,240 g ha^{-1} and Calisto {2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione} (Syngenta Agrochemical Company, Basel, Switzerland) at 210 g ha^{-1}.

2.3.1 In-Season Plant Measurements

Daily emergence notes were recorded in 5.31m zones within the center two rows of each plot. From these same zones, final plant populations were recorded after V5. Daily silk and anthesis development were monitored from 20 consecutive-plant zones in the center of each 8-row planter pass. Once 10 silks emerged ≥1cm in length and 10 anthers were visible on a tassel, plants were considered silked and tasseled, respectively. Following the completion of 50% silking (R1), 10 consecutive earleaves from plants of similar size and spacing were harvested, dried (60°C for 5-7 days), ground, and passed through a 1-mm sieve, and analyzed for N concentrations. Estimates of leaf chlorophyll content were made using SPAD-502 meters (Spectrum Technologies, Aurora, IL) on the middle of the top collared leaf (before R1) or earleaf (after R1) of 10 consecutive plants within each 20-plant zone. SPAD measurements were taken near V8, V10 to V12, and R2 to early R3. SPAD recordings for 2017 occurred on 26 June, 7 July, and 11 Aug. and for 2018 were recorded on 18 June, 28 June, and 24 July for each V8, V10 to V12, and R2 to R3 growth stage, respectively.

At physiological maturity (R6; black layer) the same plants used for SPAD were harvested for yield component determination, while in 2018 stover and cob weights were also measured to determine whole-plant biomass. For yield components, 20 ears (including an additional 10 ears from consecutive plants beyond the biomass zone) were shelled, weighed, and counted to derive mean kernel number $plant^{-1}$ and mean individual kernel weight (0% H_2O). Plant biomass at maturity was partitioned into stover (leaves, stems, and husk), grain, and cob. Biomass ears were shelled, separating grain from cobs to be dried and ground to pass through a 1-mm sieve for N concentration analysis. Due to resource constraints, cob N analysis was limited to a single replication. Grain, stover, and cobs were dried (60°C for 5-7 days), weighed, ground, passed through a 1-mm sieve and analyzed. Nutrient concentrations, biomass accumulation, harvest indexes, N uptake accumulation, N fertilizer efficiencies, and grain component data were derived from these plants. Kincaid (Kincaid Equipment Manufacturing Corporation, Haven, KS) plot combine harvest of the center two rows of each 8-row plot was used to estimate harvest moisture and grain yield (adjusted to 15.5% H_2O).

NUE, NRE, and NIE are derived using Eq. [1 to 3], respectively, and were only estimated in 2018 (because a zero N control treatment was added that year). GY_{Nfert} is the grain yield of plots receiving N, $GY_{Nunfert}$ is the grain yield of non-fertilized control plots, TNU_{Nfert} is the total N uptake in above ground biomass of N fertilized plots, $TNU_{Nunfert}$ is the total N uptake in above ground biomass of non-fertilized control plots, and $\Delta_{Napplied}$ is the difference in fertilizer rate from the N fertilized plot and the non-fertilized plot.

$$\text{Eq. [1]} \qquad \text{NUE} = \frac{\text{GY}_{\text{Nfert}} - \text{GY}_{\text{Nunfert}}}{\Delta_{\text{N applied}}}$$

$$\text{Eq. [2]} \qquad \text{NRE} = \frac{\text{TNU}_{\text{Nfert}} - \text{TNU}_{\text{Nunfert}}}{\Delta_{\text{N applied}}}$$

$$\text{Eq. [3]} \qquad \text{NIE} = \frac{\text{GY}_{\text{Nfert}} - \text{GY}_{\text{Nunfert}}}{\text{TNU}_{\text{Nfert}} - \text{TNU}_{\text{Nunfert}}}$$

2.4 Statistical Analysis

Statistical analysis was conducted using SAS 9.4 (SAS Institute, Cary NC). Homogeneity of variance between years was not met as the majority of variables showed a p-value <0.01 for year interactions (Carmer et al., 1969). Therefore, years 2017 and 2018 were analyzed and reported independently. Analysis of variance was conducted using PROC GLIMMIX with mean separation being performed with an LSMEANS statement. The mean of the two zero N plot responses per rep in 2018 were utilized in Eq. [1 to 3]. Two datasets were created; the first, referred to as Method 1, compared two placements (5x5 and 10x5), three N rates (34, 101, and 202 kg N ha^{-1}), and the interactions between placement and rate as a two by three factorial. The second dataset, referred to as Method 2, compared six placements (5x5, 5x13, 5x20, 10x5, 10x13, and 10x20), two N rates (101 and 202 kg N ha^{-1}), and their interactions as a six by two factorial. The two methods of determining placement and rate consequences were selected as the best possible combinations for examining system-relevant interactions between placement and rate; statistical analyses involving all 17 to 18 treatments simultaneously could not be implemented into a main effects contrast analysis when the chosen treatments weren't fully balanced (Littell et al., 2006).

Unlike Method 2, Method 1 included the 34 kg N ha^{-1} rate that represented a "typical" (<20%) starter fertilizer control rate that farmers would employ in continuous corn production when they don't apply pre-plant N and/or pre-emerge broadcast N in combination with residual herbicides. Because of the additional low N rate, Method 1 is the primary method reported. Method 2 is only reported for grain yield and yield components to give insight into how additional placements influenced grain yield. A full treatment response summary is provided in Appendix A. Treatment, placement, and rate were considered fixed effects. Block was treated as a random effect. An α <0.05 was considered significant for treatment, placement, or rate effects.

Method 1 placement by rate interactions was found for V12 SPAD, earleaf N%, cob N uptake, and grain yield in 2018. Plant parameter response interactions were not observed in 2017 for Method 1. Method 2 placement by rate interactions were found for kernel weight in both 2017 and 2018 and kernel number $plant^{-1}$ and grain yield in 2018. All other variables are presented as placement and/or rate means while those variables with significant interactions are reported for both means and individual treatment responses.

2.5 Results

2.5.1 Weather

Individual growing season precipitation, mean temperature, and cumulative growing degree days (GDD_C; base 10°C) were recorded from a nearby weather station (Table 2.2). The vegetative growth period (May, June, July) received 163mm more precipitation in 2017 and 73mm less precipitation in 2018 when compared to the 30-year mean. The grain filling period (Aug. and Sept.) recorded just 1.5mm less precipitation in 2017 and 82.2mm more precipitation in 2018 compared to the 30-year mean. The mean growing season (May to Sept.) precipitation was 161.4mm and 9.3mm greater than the 30-year mean for 2017 and 2018, respectively (Table 2.2).

Temperatures were near normal in 2017 and warmer than normal in 2018. The 2018 growing season experienced 186 more GDD_c than the 30-year mean with the vegetative and reproductive growth periods accumulating 118 and 68 more GDD_c than the 30-year mean, respectively (Table 2.2). Above-average May temperatures in 2018 were the primary factor for the increase in GDD_c during vegetative growth while Aug. and Sept. were slightly above historic temperatures during grain fill.

Detailed weather information regarding the 4 days before planting (days -4 to -1), the day of planting (day 0), and the 10 proceeding days (days 1 to 10) are reported for precipitation, temperature, and GDD_c for both years (Table 2.3). Planting conditions were sub-optimal in 2017 with nearly 40mm of rain recorded 3 to 4 days prior to planting. Planting proceeded in these somewhat marginal soil conditions because of concerns about further delayed planting. In 2018, planting occurred when soil was close to field capacity in more ideal conditions. Although each year featured a dry period near planting, N toxicity issues were not evident in either year. The lack of N toxicity was likely a result of the ample soil moisture at the time of planting in 2017 and above-normal precipitation following planting in 2018.

Table 2.2. Cumulative precipitation, mean temperature, and cumulative growing degree days (GDD_c; base 10°C) for each month of the May-September growing season in 2017, 2018, and the historic 30-year mean (30-year; 1988-2017) located near West Lafayette, Indiana at the Agronomy Center for Research and Education (ACRE) facilities.

	Precipitation (mm)			Mean Temperature (°C)			Cumulative (GDD_c)		
Month	2017	2018	30-year	2017	2018	30-year	2017	2018	30-year
May	174.5	94.2	121.1	15.1	20.8	16.4	192.8	335.0	235.4
June	139.7	126.2	122.8	21.9	22.6	21.5	353.9	372.8	347.0
July	203.5	61.5	110.9	22.8	22.4	22.7	398.3	382.2	389.8
August	122.2	154.9	95.1	19.9	22.6	21.8	313.3	392.2	365.8
September	49.3	100.3	77.9	19.0	20.4	18.2	281.1	311.1	269.1
5-Month Total	**689.2**	**537.1**	**527.8**	**19.74**	**21.76**	**20.12**	**1,539.4**	**1,793.3**	**1,607.1**

Table 2.3. Daily precipitation, mean temperature, and growing degree days (GDD_C; base 10°C) for the four days prior to planting (days -4 to -1), the day of planting (day 0), and the ten proceeding days from planting (days 1 to 10) for 2017 and 2018 in West Lafayette, Indiana at the Agronomy Center for Research and Education (ACRE) facilities.

	Daily Precipitation		Mean Temperature		Growing Degree Days	
	(mm)		(°C)		(GDD_C)	
Days from Planting	2017	2018	2017	2018	2017	2018
-4	19.1	0.0	14.4	16.4	4.4	7.2
-3	18.0	0.0	17.8	19.4	7.8	9.4
-2	0.0	5.1	14.2	20.6	5.0	10.6
-1	0.0	0.0	16.7	20.3	6.7	10.6
0	0.0	0.0	17.5	19.7	7.8	10.0
1	4.1	0.3	13.9	16.7	3.9	6.7
2	0.0	0.0	13.1	20.8	3.9	11.1
3	7.9	8.9	18.6	25.3	8.9	14.4
4	0.0	15.0	18.3	18.9	8.3	8.9
5	1.3	0.0	19.7	19.2	10.0	9.4
6	0.5	0.0	19.7	21.7	10.0	11.7
7	0.0	10.7	18.1	18.1	8.3	8.3
8	0.0	0.0	17.5	20.3	7.7	10.6
9	0.0	0.0	18.9	18.3	8.9	8.3
10	0.0	0.3	20.8	21.4	11.1	11.7
15-Day Total	**50.9**	**40.3**	**17.3**	**19.8**	**112.7**	**148.9**

2.5.2 Plant Establishment and Growth Rates

Final plant establishment and rate of emergence was monitored to access potential seedling toxicity. In 2017, Method 1 found a 1,900-plant ha^{-1} stand reduction for the 10x5 band placement relative to the 5x5 band placement while differences were not detected in 2018 (Supplemental Information Table 2.10). Plant establishment was not influenced in either year for Method 2 analysis (Table A.6). Rate of emergence was not impacted by Method 1 or 2. However, less GDD_c were needed for plants to reach 50% and 90% emergence in 2018 relative to 2017 (Table A.8 and A.9).

2.5.3 SPAD

A SPAD meter estimates chlorophyll content in the leaves by recording leaf spectral transmittance (Fox and Walthall, 2008) which can be used to predict leaf N concentration as SPAD and leaf N concentration are highly correlated (Markwell et al., 1995). SPAD treatment means were not influenced by planter-applied N placement in 2017 and 2018 or by N rate in 2017 at V8, V10 to V12, or R2 to R3. At the R2 to R3 stage in 2018 the 101 kg N ha^{-1} N rate improved SPAD by 6.7 units over the 34 kg N ha^{-1} planter N rate, while the leaf SPAD levels at the 202 kg N ha^{-1} rate were not significantly different from the other two rates (Table 2.4).

Table 2.4. Method 1. Vegetative (V8 and V10 or V12) and reproductive (R2-R3) stage SPAD for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	SPAD					
	(V8) 6/26/17	(V12) 7/7/17	(R2-R3) 8/11/17	(V8) 6/18/18	(V10) 6/28/18	(R2-R3) 7/24/18
5x5	48.4	52.3	54.9	45.4	45.9	53.5
10x5	47.9	53.6	54.0	46.5	44.4	51.2
34	47.1	52.4	54.7	44.8	44.1	49.0 **b**
101	48.1	53.1	54.4	46.7	46.5	55.7 **a**
202	49.5	53.3	54.4	46.4	44.8	52.1 **ab**

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

2.5.4 Grain Yield and Yield Components

Grain yields averaged across all treatments included for Method 1 were 14.06 and 12.26 Mg ha^{-1} for 2017 and 2018, respectively (Table 2.5). Reduced yields in 2018 are indicated to be associated with a reduction in mean kernel number of 54 kernels pl^{-1} as well as mean kernel weight of 40 mg kernel^{-1} when compared to 2017. At the higher yields recorded in 2017, we did not observe N placement or planter applied N rate differences to grain yield. However, in 2018 the 101 kg N ha^{-1} planter applied N rate yielded more than the 34 and 202 kg N ha^{-1} planter applied rates by 1.70 and 1.15 Mg ha^{-1}, respectively (Table 2.5). Planter applied N at 101 kg ha^{-1} increased kernel number by 69 and 54 kernels pl^{-1} relative to the 34 and 202 kg N ha^{-1} rates, respectively (Table 2.5). Kernel weights were 23 mg kernel^{-1} higher with 101 kg N ha^{-1} compared to 202 kg N ha^{-1}, while kernel weights with the 34 kg N ha^{-1} rate applied at planting were not different from both higher rates. Although both kernel number and kernel weight were unaffected by planter N placement, grain yield was improved 0.78 Mg ha^{-1} with the nearest 5x5 placement over 10x5 associated with a non-significant numeric increase in kernel number.

Harvest moisture was lowest with the 101 kg N ha^{-1} rate in both 2017 and 2018 (Table 2.5). The reduction in moisture was 0.4% in 2017 and 1.6% in 2018 (Table 2.5). The greater reduction in 2018 harvest moisture with the 101 kg N ha^{-1} rate is in part an artifact of the overall higher harvest moisture associated with earlier harvest of less dry (grain) plants for the 2018 growing season.

In 2018, an N placement by rate interaction was observed with Method 1 analysis for grain yield. The 5x5 placement position at 101 kg N ha^{-1} treatment produced the greatest yield at 13.67 Mg ha^{-1} which was statistically similar to 5x5 at 34 kg N ha^{-1}, 10x5 at 101 kg N ha^{-1}, and 10x5 at 202 kg N ha^{-1} (Table 2.6). The planter N banding placement of 5x5 at 101 kg N ha^{-1} yielded 1.97 Mg ha^{-1} more than 5x5 at 202 kg N ha^{-1} and 3.04 Mg ha^{-1} more than 10x5 at 34 kg N ha^{-1}.

Table 2.5. Method 1. Kernel number plant^{-1}, mean individual kernel weight (0% H_2O), harvest moisture, and grain yield (15.5% H_2O) for 2017 and 2018 and harvest index for 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Kernel Number —(kernels pl^{-1})—		Kernel Weight —(mg kernel^{-1})—		Harvest Moisture ————(%)————		Harvest Index	Grain Yield ——(Mg ha^{-1})——	
	2017	2018	2017	2018	2017	2018	2018	2017	2018
5x5	515	469	309	273	18.7	22.5	55.9	14.17	12.65 **a**
10x5	512	451	319	275	18.8	22.3	55.8	13.95	11.87 **b**
34	505	431 **b**	316	270 **ab**	19.0 **a**	23.3 **a**	56.6	14.30	11.48 **b**
101	514	500 **a**	309	287 **a**	18.6 **b**	21.7 **b**	55.9	13.18	13.18 **a**
202	521	446 **b**	318	264 **b**	18.7 **ab**	22.0 **ab**	54.9	14.07	12.03 **b**

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

Table 2.6. Method 1. Placement by rate interaction differences on V10 SPAD, R1 earleaf N concentration, R6 cob N uptake, and final grain yield (15.5% H_2O) for 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement†	Planter N Rate	SPAD V10	R1 Earleaf N	R6 Cob N Uptake	Grain Yield
DepthxDist.	kg N ha^{-1}	6/28/18	(%)	(kg N ha^{-1})	(Mg ha^{-1})
5x5	34	46.0 **a**	2.46 **ab**	10.7 **a**	12.34 **abc**
5x5	101	47.2 **a**	2.73 **a**	10.3 **a**	13.67 **a**
5x5	202	44.2 **ab**	2.32 **ab**	8.9 **ab**	11.70 **bc**
10x5	34	42.3 **b**	2.23 **ab**	8.2 **b**	10.63 **c**
10x5	101	45.8 **ab**	2.11 **b**	9.3 **ab**	12.69 **ab**
10x5	202	45.2 **ab**	2.50 **ab**	9.2 **ab**	12.29 **abc**

†Planter banded N at a depth from the soil surface of 5 or 10cm at a distance from the seed row of 5cm at banded at-plant (AP) N rates of 34, 101, or 202 kg N ha^{-1}

Mean grain yields for Method 2 (N placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20) were 13.96 and 12.01 Mg ha^{-1} in 2017 and 2018, respectively (Table 2.7). Like Method 1 analysis, the reduction in yields from 2017 to 2018 was correlated with mean kernel number and kernel weight reductions of 69 kernels pl^{-1} and 46 mg kernel^{-1}, respectively. In contrast to Method 1 results, Method 2 suggests a significant placement influence in 2018 for kernel number (Table 2.7). The closest 5x5 placement increased kernel number by 56 kernels pl^{-1} relative to the furthest 10x20 placement and by 79 kernels pl^{-1} relative to 5x13. The differences in kernel number resulted in final grain yields trending similarly as 5x5 produced greater yield than 5x13 and 10x20 by 1.60 and 1.29 Mg ha^{-1}, respectively. In 2018, planter banding 101 kg N ha^{-1} improved kernel weight 10 mg kernel^{-1} and final grain yield at 0.64 Mg ha^{-1} versus 202 kg N ha^{-1} (Table 2.7). The additional placements included in Method 2 found the 101 kg N ha^{-1} planter N rate superior to 202 kg N ha^{-1} which was similar to the response found in Method 1. Differences in harvest moisture were not detected in the Method 2 comparison. Overall, 2018 results from both Method 1 and 2 indicate multiple possible advantages (i.e. kernel weight, harvest moisture, and grain yield) for planter applications of 101 kg N ha^{-1} banded near seeding (i.e. 5cm from the seed row).

In 2018, a placement by rate interaction for grain yield was observed with Method 2 analysis. For Method 2, the 5x5 at 101 kg N ha^{-1} treatment produced the greatest yield at 13.67 Mg ha^{-1} which was 2.06 to 3.32 Mg ha^{-1} significantly higher than 5x13 at 101 kg N ha^{-1}, 5x13 at 202 kg N ha^{-1}, 10x13 at 101 kg N ha^{-1}, 10x13 at 202 kg N ha^{-1}, and 10x20 at 202 kg N ha^{-1} treatments (Table 2.8). However, the 5x5 at 101 kg N ha^{-1} was not superior to 5x5 at 202 kg N ha^{-1}, 5x20 at 101 kg N ha^{-1}, 5x20 at 202 kg N ha^{-1}, 10x5 at 101 kg N ha^{-1}, 10x5 at 202 kg N ha^{-1} and 10x20 at 101 kg N ha^{-1} (Table 2.8). In general, 2018 treatments with a 13cm placement from the row yielded poorly at both 101 and 202 kg N ha^{-1} at-plant rates along with the deepest and furthest placed treatment (10x20) at 202 kg N ha^{-1}.

Table 2.7. Method 2. Kernel number plant^{-1}, mean individual kernel weight (0% H_2O), harvest moisture, and grain yield (15.5% H_2O) for 2017 and 2018 and harvest index for 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Kernel Number —(kernels pl^{-1})—		Kernel Weight —(mg kernel^{-1})—		Harvest Moisture ——(%)		Harvest Index ——(%)——	Grain Yield ——(Mg ha^{-1})——	
	2017	2018	2017	2018	2017	2018	2018	2017	2018
5x5	524	488 **a**	307	273	18.6	21.8	55.0	13.81	12.82 **a**
5x13	522	409 **c**	325	262	18.3	21.7	54.2	14.24	11.22 **c**
5x20	517	454 **abc**	310	274	18.5	22.1	55.0	14.05	12.58 **ab**
10x5	511	463 **ab**	320	279	18.7	21.9	55.8	14.06	12.49 **ab**
10x13	519	452 **abc**	320	270	18.2	22.3	55.8	13.97	11.56 **abc**
10x20	516	432 **bc**	320	271	18.2	22.0	54.9	13.58	11.53 **bc**
101	521	453	321	276 **a**	18.4	21.8	55.5	13.90	12.33 **a**
202	515	444	313	266 **b**	18.4	22.1	54.7	14.01	11.69 **b**

†ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table 2.8. Method 2. Placement by rate interaction differences on mean individual kernel weight (0% H_2O) in 2017 and 2018 and kernel number plant^{-1} and grain yield (15.5% H_2O) in 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement†	Planter N Rate	Kernel Weight		Kernel Number	Grain Yield
		(mg kernel^{-1})		(kernels pl^{-1})	(Mg ha^{-1})
DepthxDist.	kg N ha^{-1}	2017	2018	2018	2018
5x5	101	321 **ab**	281 **ab**	522 **a**	13.67 **a**
5x5	202	292 **b**	262 **ab**	443 **abc**	11.69 **abcd**
5x13	101	334 **ab**	255 **b**	379 **c**	11.03 **cd**
5x13	202	317 **ab**	270 **ab**	440 **bc**	11.41 **bcd**
5x20	101	320 **ab**	279 **ab**	448 **abc**	12.26 **abc**
5x20	202	300 **ab**	268 **ab**	459 **ab**	12.90 **ab**
10x5	101	296 **ab**	292 **a**	478 **ab**	12.69 **abc**
10x5	202	344 **a**	266 **ab**	448 **abc**	12.29 **abc**
10x13	101	334 **ab**	272 **ab**	447 **abc**	11.61 **bcd**
10x13	202	305 **ab**	269 **ab**	456 **ab**	11.51 **bcd**
10x20	101	322 **ab**	279 **ab**	444 **abc**	12.70 **abc**
10x20	202	319 **ab**	262 **b**	420 **bc**	10.35 **d**

†Planter banded N at a depth from the soil surface of 5 or 10cm at a distance from the seed row of 5, 13, or 20cm at banded at-plant (AP) N rates of 101 or 202 kg N ha^{-1}

2.5.5 Flowering and Maturity N Concentrations

Earleaf N concentrations provide insight into relative plant N uptake at R1 and plant capacity to meet grain sink demands during grain fill. Earleaf N averaged 2.83-2.89% (no placement or rate differences) across planter N placement and rate combinations in 2017 (Table 2.9), just below the recommended range of 2.90-3.50% in the Tri-State Recommendations (Vitosh et al., 1995). Much lower earleaf N% was observed in 2018 (i.e. between 2.28-2.52%) where 5x5 banding improved earleaf N by 0.24% compared to 10x5 banding (Table 2.9). Earleaf N% was not influenced by planter applied N rate in either year. Planter-banded N placements' influence on earleaf N% was reinforced by a significant placement by rate interaction, since at the common at-plant N rate of 101 kg N ha^{-1} 5x5 banding was 0.62% greater than 10x5 banding (Table 2.6).

Stover and grain N% at maturity were only measured in 2018. While the 5x5 placement improved R1 earleaf N%, neither R6 stover or grain N% were influenced by placement (Table 2.9). When planter applications of 34 or 101 kg N ha^{-1} were paired with their respective sidedress rate of 168 or 101 kg N ha^{-1} grain N was improved by ~0.05% when compared to the 202 kg N ha^{-1} planter rate that did not receive sidedress N (Table 2.9). Grain N% differences suggest sidedress N may provide opportunity for increased grain N%. Mean grain, stover, and cob N concentrations were 1.05, 0.72 and 0.78%, respectively.

Table 2.9. Method 1. Flowering (R1) earleaf N concentrations for 2017 and 2018 and physiological maturity (R6) grain, stover, and cob N concentration for 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	2017 Flowering (R1) N Concentrations Earleaf	2018 Flowering (R1) N Concentrations Earleaf	2018 Maturity (R6) N Concentrations Grain	2018 Maturity (R6) N Concentrations Stover	2018 Maturity (R6) N Concentrations Cob†
	(%)				
5x5	2.83	2.52 **a**	1.03	0.70	0.79
10x5	2.89	2.28 **b**	1.06	0.73	0.76
34	2.84	2.34	1.06 **a**	0.72	0.81
101	2.88	2.42	1.07 **a**	0.75	0.74
202	2.86	2.42	1.01 **b**	0.67	0.78

†Not statistically analyzed, only one rep of data

‡ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

2.5.6 Biomass and N Uptake Accumulation

Total plant biomass and N uptake accumulation at maturity were only estimated in 2018. Biomass for each plant component (grain, stover, and cob) was always greatest with the 101 kg N ha^{-1} planter applied rate (Table 2.10). The 101 kg N ha^{-1} rate improved biomass accumulation by ~1,621 kg grain ha^{-1}, 161 kg cob ha^{-1}, and 3,042 kg total biomass ha^{-1} among both rates. Stover biomass for the 202 kg N ha^{-1} rate was not different from 34 or 101 kg N ha^{-1} rates, but the 101 kg N ha^{-1} rate produced 1,541 kg ha^{-1} more stover than the 34 kg N ha^{-1} rate (Table 2.10).

Total N uptake of fertilizer and mineralized N showed similar results (Table 2.10). The 101 kg N ha^{-1} rate was superior to both 34 and 202 kg N ha^{-1} planter rates in grain, stover, and total N uptake (Table 2.10). Mean N uptake was increased with the 101 kg N ha^{-1} at-plant application compared to both 34 and 202 kg N ha^{-1} rates by ~21.2 kg grain N ha^{-1}, ~14.2 kg stover N ha^{-1}, and ~35.5 kg total N ha^{-1} (Table 2.10). While placement did not influence biomass accumulation, cob N uptake was improved 1.2 kg ha^{-1} with a 5x5 placement (we believe this is an artifact of data variability with a single replication of cob N concentrations used for cob N accumulation calculation).

Table 2.10. Method 1. Physiological maturity (R6) biomass and N uptake accumulation in grain, stover, cob, and total for 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Maturity (R6) Biomass Accumulation				Maturity (R6) N Accumulation			
	Grain	Stover	Cob	Total	Grain	Stover	Cob	Total
	(kg ha^{-1})				(kg N ha^{-1})			
5x5	10,564	8,367	1,268	20,219	109.0	59.0	10.1 **a**	178.1
10x5	10,154	8,034	1,178	19,366	108.2	58.6	8.9 **b**	175.6
34	9,768 **b**	7,496 **b**	1,166 **b**	18,430 **b**	103.7 **b**	53.6 **b**	9.4	166.7 **b**
101	11,408 **a**	9,037 **a**	1,326 **a**	21,771 **a**	122.0 **a**	68.0 **a**	9.8	199.8 **a**
202	9,806 **b**	8,057 **ab**	1,164 **b**	19,028 **b**	98.9 **b**	54.1 **b**	9.0	162.0 **b**

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

2.5.7 N Fertilizer Efficiencies and N Harvest Index

Nitrogen uptake, N fertilizer efficiencies, and N harvest index (NHI) were only estimated in 2018. A treatment mean NUE of 45.9 (kg kg^{-1}) indicated that for every kg of fertilizer applied, 45.9 kg of additional grain was produced (Table 2.11). A mean NRE of 73.3% indicates a recovery of ~73% of the fertilizer applied into above-ground biomass. We recorded a mean N internal efficiency (NIE) of 63.6 kg grain kg^{-1} of whole-plant N uptake for these treatments. A mean NHI of 65.0% corresponds to the percentage of N allocated to the grain compared to the total N present in all above-ground biomass at maturity.

Placement never affected NUE, NRE, NIE, or NHI while the distribution of N between planting and sidedress did. The 101 kg N ha^{-1} planter N rate followed by 101 kg N ha^{-1} sidedressed improved NUE by 9.1 and 9.5 kg kg^{-1} over the 34 and 202 kg N ha^{-1} planter rates, respectively (Table 2.11). Similar to NUE, NRE was improved by 18.5% with the 101 kg N ha^{-1} planter rate compared to the 34 kg N ha^{-1} rate and 21.2% relative to the 202 kg N ha^{-1} rate (Table 2.11). The true split 50:50 N management strategy between planter applied N and V5 to V6 sidedress timings allowed for plants to recover more N and utilize the recovered N more efficiently to produce more grain per kg of fertilizer applied. Neither NIE or NHI were influenced by N rates applied at planting (Table 2.11).

Table 2.11. Method 1. Physiological maturity (R6) N use efficiency (NUE), N recovery efficiency (NRE), N internal efficiency (NIE), and N harvest index (NHI) for 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	NUE	NIE	NRE	NHI
	(kg kg^{-1})		(%)	
5x5	46.8	64.6	73.8	65.2
10x5	44.9	62.5	72.7	64.8
34	42.8 **b**	63.3	67.6 **b**	65.8
101	51.9 **a**	61.4	86.1 **a**	64.6
202	42.4 **b**	66.1	64.9 **b**	64.6

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

2.6 Discussion

While little research has been conducted utilizing planter applied N that supplies up to full-season N rates, at-plant N applications (i.e. broadcast or banded N applications within ~48 hours of planting) are commonly employed. For example, the literature has compared single at-plant versus split N applications between at-plant and sidedress, similar to our 101 kg N ha^{-1} at-plant rate followed by a V5 to V6 sidedress application of the same rate. Niehues et al. (2004) found planter applied rates of a UAN solution from 34-138 kg N ha^{-1} banded 5cm by 5 cm (from seeding) followed by an early sidedress application balancing total N to 168 kg N ha^{-1} achieved similar grain yields while an improvement in corn yield was found between treatments receiving starter fertilizer and a single sidedress application in continuous no-till corn. Our 2018 results disagree with Niehues as we found an increase in grain yield with a 101 kg N ha^{-1} rate over the 34 kg N ha^{-1} at-plant rate. Our 2018 results also disagree with Kovács et al. (2015) who found increased yield with NH_3 supplied entirely by pre-plant applications versus early sidedress timed applications following starter fertilizer in a corn-soybean rotation. Szulc et al. (2020) found no placement yield influence for at-plant N applied at 100 kg N ha^{-1} placed 5cm from seeding and 5, 10, or 15cm deep confirming the neutral grain yield response to placement that we found for similar and higher N rates at the 5 and 10cm depth in each year. In our research, yield was never reduced and occasionally increased, with planter banded N at 101 or 202 kg ha^{-1} compared to 34 kg N ha^{-1}, suggesting that in some environments and planting conditions planter applied rates up to 202 kg N ha^{-1} can be utilized near seeds without negative plant stand or growth consequences. A minor stand reduction of 1,900 plants ha^{-1} was observed with 10x5 placement compared to 5x5 in 2017. However, this reduction did not translate to reduced grain yield. These results disagree with Vyn and West (2009) who researched 56, 112, and 224 kg N ha^{-1} banded at-planting and found progressively reduced stands as banding neared seeding from 25, 13, and 0cm at the 224 kg N ha^{-1} rate.

According to Randall et al. (2003), we would expect split N applications to perform best in years when early vegetative stage (May and June) precipitation is above normal; in 2017 May to June precipitation was 70.3mm greater than the 30-year mean and yet split N had no yield advantage. In 2018, May to June precipitation was 23.5mm less than the 30-year mean and we observed N timing treatment separations. Notably, the 50:50 split treatment was superior in many variables including NRE, NUE, N uptake, and grain yield when compared to both the 34 and 202 kg N ha^{-1} at-plant rates. The grain filling period (Aug. to Sept.) precipitation seemed much more influential, then vegetative rainfall from May to July, with 1.5mm less and 82.2mm more precipitation recorded during Aug. and Sept. compared to the 30-year mean in 2017 and 2018, respectively. We also know from Morris et al. (2018) that receiving precipitation shortly after N application strongly influences NRE and grain yield differences. Within 4 days of planting only 12mm of precipitation was recorded in 2017 compared to 24.2mm in 2018, potentially reducing the effectiveness of planter banding 101 and 202 kg N ha^{-1} in 2017 but favoring the same planter-banded rates in 2018. Within 72 hours following V5-V6 sidedress at least 10mm of precipitation was recorded.

Aside from the possible influence of precipitation timing, the reduced treatment separations in 2017 could be due to N being less of a yield-limiting factor in 2017 as earleaf N% was lower in 2018 which was paired with reduced grain yields in 2018 (12.26 Mg ha^{-1}) versus 2017 (14.06 Mg ha^{-1}). This increased N stress could be associated with continuous corn production and a depleting soil supply of N was greater in 2018 with that being the 3rd year of monocropping corn. This theory is reinforced by R1 earleaf N% where 2017 and 2018 mean concentrations were 0.04% and 0.50% below the minimum recommended sufficiency, respectively. Alternatively, it is possible that the increased daily GDD_c accumulation (+2.4 GDD_c day^{-1} in 2018 compared to 2017) just prior to and following planting in 2018 led to quicker growth of plants and a higher at-plant N rate promoted more early-season growth in 2018 more so than in 2017. Further evidence, indicated by SPAD determinations at late R2, show the 101 kg N ha^{-1} rate maintained leaf greenness and possibly improved post-silking N uptake compared to the 34 kg N ha^{-1} rate. In a corn following corn cropping system in west-central Indiana, Camberato and Nielsen (2019) recommend total N rates are ~45 kg N ha^{-1} greater than what we employed. Our total N rates also matched those for similar trials funded by John Deere in two other state for 2017 and 2018. Continuous corn production possibly mined soil N supplies granting an advantage to N management strategies that promoted early growth and reduced N loss resulting in increased total N uptake in 2018 as we wanted total N rates to remain the same between years. Banded 5x5 starter fertilizer research by Camberato et al. (2016) found improved yield with continuous corn in 7/21 site-years (6/7 responses in no-till) and in a corn-soybean rotation, 7/15 site-years responded. Additional research focused on planter applied N systems at moderate to high N rates should consider no-till systems in continuous corn.

2.7 Conclusion

Prior to the beginning of this trial, we first hypothesized that safe and yield-effective planter applied fertilizer placements will improve yield at higher than normal N rates commonly employed at the 5cm x 5cm (from seed placement) starter fertilizer placement. This hypothesis was proven wrong as common starter fertilizer placements (10x5 assuming a 5cm seeding depth) were safely utilized at even the highest at-plant N rates in each year of this trial.

Secondly, we hypothesized that planter applied 202 kg N ha^{-1} rates would decrease yield as N loss and potential seedling toxicity would reduce plant stands and inhibit early-season growth. Our second hypothesis was partly proven wrong as the 202 kg N ha^{-1} planter applied rate never reduced plant stand. However, a grain yield reduction was observed (averaged across 5x5 and 10x5 placements) in 2018 with the 202 kg N ha^{-1} rate compared to the 101 kg N ha^{-1} rate while the 202 and 34 kg N ha^{-1} planter applied rates were statistically similar.

Our specific objectives of the study were to (i) determine if planter N placement and or rate influenced plant growth rates, biomass accumulation and/or grain yield, and (ii) investigate if alternative placements and non-typical rates could be safely utilized by modern planters to improve both N application efficiency and plant responses in a conventional tillage continuous corn cropping system. Regarding the objectives of this study, (i) planter N placement was much less influential on corn biomass and grain yield than N rate was in 2018 (N rate was also the largest factor driving N uptake and NRE), and (ii) a traditional starter fertilizer placement (equal to 10x5 in our treatments assuming 5cm seeding depth) and higher than typical N rates (such as the 101 kg N ha^{-1} we employed) can improve corn yield in a continuous corn cropping system where no pre-plant N is applied.

In 2018, the 101 kg N ha^{-1} rate was superior in most measured plant variables over the 34 kg N ha^{-1} rate and, to a lesser extent, relative to the 202 kg N ha^{-1} rate. The intermediate 101 kg N ha^{-1} rate improved corn biomass accumulation, total N uptake, NUE, NRE, KN, KW, and grain yield in 2018.

Limited N placement differences in 2017 reduced our potential understanding of the best planter applied N rate for this conventional-till, corn following corn cropping system. Placement differences between 5x5 and 10x5 systems were mostly insignificant, confirming that a common 5cm x 5cm starter fertilizer placement can safely deliver UAN at ≥101 kg N ha^{-1} given adequate soil moisture and/or precipitation following planting. The relatively new idea of increased N rates applied at-planting can reduce nutrient application passes and seems to be a risk-averse N management strategy capable of increasing N efficiency (especially in weather or time-constrained spring N application opportunities). High rate planter applied N provides an opportunity to improve early season growth and development leading to an overall increase in N uptake and fertilizer recovery while improving grain yield and reducing N loss to the environment. Additional research on planter-applied N should focus on alternate soil types, tillage systems, and weather conditions surrounding planting as ammonia toxicity issues could occur with planter applied N management strategies when environmental conditions and N applications expose corn seeds or seedling roots to high concentrations of ammonium.

2.8 Acknowledgments

A special thank you to Dr. Tony Vyn's cropping system crew during the 2017 and 2018 growing seasons for their careful and hard work both in collection and processing samples to acquire this dataset. Also, thank you to John Deere for their financial support of this project and the Indiana Corn Marketing Council for additional support in 2018-2019 via a 12-month Gary Lamie Graduate Award that provided a regular graduate assistantship.

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2.10 Supplemental Information

Supplemental Information Table 2.12. Method 1. Post V5 final plant population for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Final Plant Populations ———(Plants ha^{-1})———	
	2017	2018
5x5	83,000 **a**	76,000
10x5	81,100 **b**	77,400
34	81,900	76,600
101	82,300	76,400
202	82,000	77,300
Mean	**82,000**	**76,700**

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

CHAPTER 3. PLACEMENT CONSEQUENCES IN SPLIT-NITROGEN SIDEDRESS APPLICATIONS FOR CORN YIELDS AND NITROGEN EFFICIENCIES

3.1 Abstract

Sidedress nitrogen (N) management in corn (*Zea mays* L.) continues to be a common farming practice in the Eastern Corn Belt. While the influence of sidedress timing, placement, rate, and source have been studied, inconsistent results to N applications arising from genetic, environmental, and management interactions have made generalizable recommendations difficult. A two-year (2017 and 2018) field-scale study conducted near La Crosse, Indiana compared a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112) and 224 (AP_224) kg N ha^{-1} versus split applications between at-plant N and sidedress applications of urea ammonium nitrate (UAN) at V5 or V12 timings, or of broadcast urea at the V8-stage. All split N treatments received a total of 202 kg N ha^{-1} in a 55:45 split between at-plant and sidedress. The V5 and V12 UAN applications were either surface streamed (str) or subsurface injected (inj). In 2017, both AP_224 and V12_str (14.39 and 14.40 Mg ha^{-1}, respectively) yielded 0.91 Mg ha^{-1} more than V12_inj, although this gain was not accompanied by increased N recovery efficiency (NRE). When total fertilizer N was ≥202 kg ha^{-1} in 2018, N timing (AP, V5, V8, and V12) didn't impact grain yield. Analyses of streaming versus injection application methods (averaged over V5 and V12 timings) found streaming increased grain yield by 4.6% and N use efficiency (NUE) by ~4.0 kg grain kg^{-1} N applied in 2017, but there was no apparent yield or NUE gain with surface streaming in 2018. Both NUE and NRE were higher with AP_112 than all treatments other than V5_str in 2018. In this two-year study, split N sidedress applications at either V5, V8, or V12 generally responded similarly to full-rate at-plant applications involving 22 kg ha^{-1} more total N. Split N approaches may have contributed more to corn yield and NRE improvements in growing seasons that experienced more in-season N losses than those realized in this research. However, when split N was adopted, the N placement employed at sidedressing impacted corn yield and N efficiency more than the N timing.

3.2 Introduction

The most recent decade has challenged farmers as low commodity prices followed the record highs realized earlier. The combination of low prices and increasing production cost has incentivized growers into experimenting with alternative crop management strategies. Nitrogen (N) management is of high importance as N is a leading input cost for corn growers throughout the Midwest and is critical for high yields. Applying too much N (e.g. exceeding the economic optimum N rate: EONR) leads to unacceptable pollution of water sources and the atmosphere; applying too little results in sub-optimal yields and sharply lower profits. Improving crop use of applied N would increase N use efficiency (NUE) as well as N recovery efficiency (NRE). More effective N utilization could allow for increased yields while reducing input cost and potential N loss to the environment. Technological advancements such as high clearance machinery, and multiple N application placement methods to choose from (i.e. surface banded, broadcast, sub-surface banded, etc.) offer growers options that can deliver N efficiently and effectively throughout the vegetative growth period. These modern solutions may prove valuable in improving the way farmers manage inputs in high yielding corn.

In the Midwest, corn production typically relies on the bulk of a total N rate applied as either pre-plant (fall/spring), at-plant, or delayed until a sidedress application can be made (so-called "early sidedress", commonly between the V4 to V6 stage). Research from Argentina comparing at-plant and V6 sidedress of urea found sidedress applications reduced NO_3^- leaching and gaseous losses (Sainz Rozas et al., 2004). Wells et al. (1992), studied two urea sources and ammonium nitrate broadcast on the surface comparing at-plant and V5 sidedress and observed that V5 timing improved flowering (R1) earleaf N% as well as grain yield for each source. Theoretically, in-season N applications provide increased N uptake potential as there is a reduced period of N exposure to leaching and volatilization when compared to pre-plant and at-plant systems. Maciel de Oliveria et al. (2018) reported greater corn N recovery with in-season applications compared to at-plant in a labeled ^{15}N study in Brazil.

Although most in-season N is applied between V4 to V6, there are opportunities to further enhance both plant response and fertilizer use with V10 to V14 (late sidedress) applications when adequate N is supplied upfront so as not to compromise early growth and development. A recent review paper covering the U.S. (9 publications), China (3 publications), Kenya (1 publication), and Germany (1 publication) compared late-season N applications and found no yield advantage between early (pre-V6) or late (post-V10) timings even when >50% of the total N was supplied post-V10 (Fernandez et al., 2019). Similarly, Scharf et al. (2002), concluded from a 28-site year study in Missouri that N timing did not influence yield between a single at-plant and 100% sidedress application before V11, while minor (<3%) yield losses occurred when N was delayed to V12 to V16. In agreement with Scharf's results, Jaynes and Colvin (2006) found a loss of 0.80 and 1.61 Mg ha^{-1} in 2002 and 2004, respectively when a 50:50 split N application of UAN at 138 kg N ha^{-1} was applied at emergence and V16 instead of in a single postemergence application. For each of these previously mentioned studies, since the in-season N applied ranged from 50-100% of the total-season N rate applied, it is possible that N related stress may have occurred prior to sidedress applications-thus reducing yield potential.

Contrary to the previously mentioned studies, a large 49-site year study covering much of the U.S. found split N increased grain yield NUE relative to at-plant applications at the economic optimum N rate (EONR) (Kitchen et al., 2017). In that multi-state study, ammonium nitrate was surface-applied at 5 N rates to both at-plant and split sidedress (V7 to V9) applications where split N provided >50% of the total N rate (Kitchen et al., 2017).

Late-season sidedress N applications have been investigated as late as R1, which provides an opportunity for additional crop N assessment opportunities before the planned application is made. Rescue or planned N applications at R1 can be equally as productive as early applications in N uptake, NRE, and grain yield if greater than half the total N rate is supplied before the V3 stage (Mueller and Vyn, 2018). Scharf et al. (2002) concluded that there were only minor to moderate (<15%) reductions when all fertilizer N was delayed until R1. Visibly N stressed plants have recovered grain yield with late-vegetative and R1 stage N applications; however, unfortunately, once N stress reduces biomass accumulation, the maximum yield potential has been diminished (Binder et al., 2000; Janes and Colvin 2006; Muller and Vyn, 2018). These studies provide insight into the environments and management considerations for utilizing early, late, and/or R1 applications of N to potentially improve N recovery and/or grain yield.

Sidedress N fertilizer placements include surface broadcast, surface banding, and subsurface banding. Subsurface applications have generally been the standard N management strategy but modern herbicide and equipment technologies have led to greater adoption of no-till practices over the last several decades (Wade et al., 2015). Conservation tillage adoption has likely led to the use of more surface-applied fertilizer to minimize soil disturbance. Additionally, surface applications of liquid N fertilizers have many placement options; e.g. broadcast, mid-row banded, or the use of the Y-Drop™ (360 Yield Center, Morton, IL) system which places N on both sides of the corn rows.

Each application method has different agronomic and in-field management advantages that differ across environments and cultural practices. Historic in-season UAN placement research conducted in Indiana observed consistently lower yields with surface broadcast compared to injected UAN (Mengel et al. 1974). Woodley et al. (2018) concluded that UAN injection improved grain yield when compared to a surface-banded approach on a Brookston clay loam in Ontario, Canada. However, the effectiveness of the Y-Drop™ system is not well researched. A single-year extension summary conducted in Michigan by Steinke and Purucker (2018) found coulter injection performed better than Y-Drop™ for UAN applied at V6 at one location and a neutral response at another.

Granular products (e.g. urea) do not offer as much flexibility and simplicity in placement as liquid solutions. Mengel et al. (1974) found that surface broadcast of urea (as well as ammonium nitrate and UAN) yielded less than subsurface injected applications of NH_3 and UAN. Fox et al. (1986) compared three N sources (ammonium nitrate, urea, UAN) that were either mid-row banded on the surface or subsurface at two timings (prior to emergence and V5-V6 sidedress) and found subsurface injection and sidedress proved to be the best combination for improved earleaf N%, N uptake, and grain yield on a Murrill silt loam in Pennsylvania. In contrast with these studies, Drury et al. (2017) compared broadcast urea and injected UAN on a Brookston clay loam in Ontario, Canada at the V6-V8 stage and observed no advantage for either placement in corn N uptake or grain yield.

Plant available N from either fertilizer or soil mineralization sources is mostly taken up as dissolved nitrate (NO_3^-) and ammonium (NH_4^+) (Brady and Weil, 2009). Plant N uptake accounts for all uptake whether that be from fertilized N or mineralized soil N. How well a plant uses and recovers fertilizer-applied N is described by N fertilizer efficiencies. Three different fertilizer efficiencies can be used to determine how well a plant uses or recovered fertilizer: N use efficiency (NUE: grain yield per unit N applied), N recovery efficiency (NRE: additional plant N uptake per unit fertilizer N relative to no fertilizer N), and N internal efficiency (NIE: grain yield per unit plant-recovered N) (Ciampitti and Vyn, 2011; Ciampitti and Vyn, 2012; Mueller and Vyn, 2017).

To calculate NRE and NUE by the difference method, unfertilized control plots are needed to account for soil mineralized N.

Approximately 65 to 75% of total N uptake occurs by R1 with a peak N uptake rate at or after V10 (Hanway, 1963; Mengel and Barber, 1974; Abendroth et al., 2011; Bender et al., 2013). Bender et al. (2013) observed peak N uptake of 7.8-8.9 kg N ha^{-1} day^{-1} occurred between V10-V14. While peak N uptake occurs in the late vegetative growth stages, N uptake continues post silking. Post silking N can account for >1/3 of the total uptake in corn hybrids (Pan et al., 1986; Mueller and Vyn, 2016), and that late-season uptake can increase plant NRE without associated grain yield gains (Mueller et al., 2017).

Targeted N applications can help to synchronize N fertilizer additions with peak plant N uptake to potentially minimize environmental loss and optimize the plant's ability to recover fertilizer N. New hybrids (i.e. those since 1990) have proven their ability to recover more post silking N (Mueller and Vyn, 2016) than older, pre-1990 hybrids as well as realizing more total N uptake and NRE (Ciampitti and Vyn, 2012). Even when post silking N uptake is improved by R1 applications, there is not always a positive correlation to increased total N uptake, NRE, or yield (Mueller and Vyn, 2018).

Water plays an integral part in N availability, plant N uptake, and grain yield. In irrigated sandy loam soils comparing surface broadcast urea at 8 rates, Maharjan et al. (2016) found split applications increasing NRE and grain yield when compared to single at-plant applications on a Hubbard loamy sand in Minnesota. Meanwhile, the same experiment in a water-limited environment resulted in a neutral response to timing. Morris et al. (2018) stated that precipitation soon after N applications was very influential in determining treatment differences with NRE in their results. When growing season precipitation is in abundance, researchers found a V10 sidedress application of urea increasing grain yield compared to a pre-plant control of the same total N rate if and only if adequate precipitation followed the application (Kaur et al., 2017).

Before beginning this trial, we hypothesized that corn yields and whole-plant N fertilizer recovery would improve with split N applications versus a single at-plant N application, especially so with late sidedress applications. We also hypothesized that coulter injection of UAN would provide increased plant N uptake and grain yield compared to surface placements in this rain-fed sandy loam environment. Our specific objectives of the study were to (i) determine if placement or timing of sidedress N influenced N uptake, N fertilizer efficiencies, and or grain yield and (ii) investigate split sidedress N strategies and their influence on N uptake, NRE, and grain yield compared to a single at-plant N application at full and reduced N rates.

3.3 Materials and Methods

A two-year rainfed field-scale experiment was conducted from 2017-2018 at the Purdue University Mary S. Rice farm (41.327°N, 86.802°W) near La Crosse, Indiana. Fields were adjacent to each other and each employed a no-till corn-soybean (*Glycine max* L. *Merr.*) rotation. The two field sites consisted primarily of a 0-1% sloping, Gilford fine sandy loam (Coarse-loamy, mixed, superactive, mesic Typic Endoaquolls) soil. Mean soil fertility (2017, 2018) derived from 15-20 cores to a 20cm depth collected before or shortly after emergence for pH, organic matter (OM), and cation exchange capacity (CEC) were 5.9 (5.8, 60), 2.4% (2.2, 2.6), 8.4 $cmol_c$ kg^{-1} (7.8, 9.0), respectively. Phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentrations were 65 mg kg^{-1} (55, 75; Mehlich-3), 161 mg kg^{-1} (160 ,163; Mehlich-3), 850 mg Mg^{-1} (780, 920), and 222 mg Mg^{-1} (212, 231), respectively. Analyses were conducted at A&L Laboratories (Fort Wayne, IN) using the recommended chemical soil test procedures for the North Central region (Denning et al., 2011).

Eight treatments consisting of a combination of 4 nitrogen (N) rates (i.e. 26, 112, 202, or 224 kg N ha^{-1}), 4 application timings (i.e. at-plant, V5, V8, or V12), and 3 in-season application methods (i.e. surface broadcast, surface banded, subsurface banded) were arranged in a randomized complete block design experiment with 4 or 5 replications (2017 and 2018, respectively). Nitrogen was applied as urea ammonium nitrate (UAN-28%) at planting (AP), V5, and V12 stages, or as urea treated with Agrotain™ (Koch Agronomic Services, Wichita, KS) at V8 (Table 3.1). All treatments received a starter fertilizer of 19-17-0 (N-P_2O_5-K_2O) at 137 kg ha^{-1} delivering 26 kg N ha^{-1} which was dribbled on the surface directly behind seed-slot closing wheels and just ahead of the press wheels on each row unit of a Case IH 2150 (CNH Industrial, Racine, WI) planter. The at-plant N rates of UAN were broadcast on the soil surface and applied on 18 May 2017 and 8 May 2018 (within two days of planting), delivering 0, 86 or 198 kg N ha^{-1} (Table 3.1). Sidedress N at V5, V8, or V12 stages (Abendroth et al., 2011) of 90 kg N ha^{-1} following the at-plant 86 kg N ha^{-1} rate plus starter N fertilizer resulted in total N rates of 202 kg N ha^{-1}. Three control treatments included an only starter fertilizer treatment (Zero) and two at-plant N rate treatments of either 86 kg N ha^{-1} rate (AP_112) or 198 kg N ha^{-1} rate (AP_224).

Sidedress N placement methods were streaming (str) of UAN at V5 (V5_str) and V12 (V12_str), surface broadcast urea at V8 (V8_urea), and subsurface injection (inj) of UAN at V5 (V5_inj) and V12 (V12_inj) (Table 3.1).

Table 3.1. Nitrogen treatments used in both 2017 and 2018. Nitrogen timings consist of surface banded starter fertilizer (SF) applied at-planting, surface broadcast at-plant (AP) N applied shortly after planting, and sidedress N applied at growth stages V5, V8, or V12. All N was supplied as 28% urea ammonium nitrate (UAN) except V8_urea which was supplied by broadcast urea treated with a urease inhibitor.

	Application Timing					
	SF	AP	V5	V8	V12	Total
Treatment†	N rate (kg N ha^{-1})					
Zero	26	--	--	--	--	26
AP_112	26	86	--	--	--	112
AP_224	26	198	--	--	--	224
V5_str	26	86	90	--	--	202
V5_inj	26	86	90	--	--	202
V8_urea	26	86	--	90	--	202
V12_str	26	86	--	--	90	202
V12_inj	26	86	--	--	90	202

†Sidedress N placement was either surface streamed (str) or by mid-row subsurface injection (inj)

The 24-row corn plots with 0.76-m row spacing at ~381m in length were planted on 16 May 2017 with DKC63-60RIB (Bayer CropScience, St. Louis, MO) at 70,000 seeds ha^{-1} and on 8 May 2018 with P0574AMXT (Corteva Agriscience, Wilmington, DE) at 75,000 seeds ha^{-1} establishing a final mean population of 70,000 plants ha^{-1} (mean of 68,000 and 72,000 plants ha^{-1} in 2017 and 2018, respectively). Sidedress N applications at V5 were applied on 13 June 2017 and 4 June 2018, V8 urea N was applied on 22 June 2017 and 15 June 2018, and V12 N was applied on 6 July 2017 and 2 July 2018. Herbicide applications to control weeds were made pre-emergence with Fultime NXT {acetochlor [2-chloro-N-ethoxymethyl-N-(2-ethy;6 methylphenyl)acetamide]/ atrazine [6-chloro-N-ethyl-N-(1-methylethyl)-1,3,5-triazine-2,4-diamine]} (Corteva Agriscience, Wilmington, DE) at 2,100 g ha^{-1} and Gramaxone (20% of active principle Paraquat, 1,1 '-dimethyl-4,4'-bipyridium dichloride) (Syngenta Agrochemical Company, Basel, Switzerland) at 3.51 L ha^{-1} with glyphosate [*N*-(phosphonomethyl)glycine] (Bayer CropScience, St. Louis, MO).

Split N streaming applications were 24 rows wide and accomplished via high clearance Hagie applicator (Hagie Manufacturing Co., Clarion, IA) equipped with Y-Drop™ (360 Yield Center, Morton, IL) streaming to the toolbar for both timings in 2017 and the V12 timing in 2018. In 2018 streaming at V5 was applied by a drop tube fitted with a streaming nozzle that evenly broadcast UAN in 5 bands between each row from a John Deere platform. V8 urea was broadcast applied with a high clearance pull-behind Chandler Model AT-FTLH EXW (Chandler Equipment Co., Gainesville, GA) spreader at 24 rows wide by a Case IH Magnum 240 (CNH Industrial, Racine, WI) tractor. Injected treatments were coulter applied with mid-row placements to the center 16 rows of each plot from a custom-built toolbar (similar to Hagie nitrogen toolbar, NTB) fitted to a 16-row high clearance Hagie (Hagie Manufacturing Co., Clarion, IA) applicator for each application timing and year.

3.3.1 In-Season Plant Measurements

Plant population was estimated from 5.31m long zones in the center two rows of each plot. Single 20-plant zones of similar size and plant spacing were established in the center of the first 12-row planter pass per plot to monitor daily silk and anthesis development. Once 10 silks emerged ≥1cm in length and 10 anthers were present on a tassel, plants were considered silked and tasseled, respectively. Following completion of 50% silking (R1), 10 consecutive earleaves outside of the silking zones were harvested, dried (60°C for 5-7 days), ground, and passed through a 1-mm sieve, and analyzed for N, P, K, Ca, Mg, sulfur (S), zinc (Zn), manganese (Mn), iron (Fe), copper (Cu), boron (B), and aluminum (Al) concentrations. Estimates of leaf chlorophyll content were made using SPAD-502 meters (Spectrum Technologies, Aurora, IL) from the middle of each earleaf of 10 consecutive plants within the silking zones. In 2017, SPAD readings were recorded on 23 Aug. (R4) while, in 2018, SPAD levels were recorded on 27 July and 31 Aug., (R2 and R5, respectively). At physiological maturity (R6; black layer) the same plants used for SPAD were harvested for whole-plant biomass measurements. An additional 10 consecutive ears from plants within the silking zone not harvested for whole-plant biomass were also used in yield component measurements. Plants for biomass measurements were partitioned into stover (leaves, stems, and husk), grain, and cob. The 20 collected ears were shelled, weighed, and counted to derive mean kernel number plant^{-1} and mean individual kernel weight (0% H_2O). Of the 20 ears, the kernels and cobs from 10 ears of the stover biomass plants were dried (60°C for 5-7 days) and ground to pass through a 1-mm sieve for N% analysis. Because of resource constraints, cob N analysis was only completed on a single rep. Stover was dried (60°C for 5-7 days), weighed, ground, passed through a 1-mm sieve and analyzed. From these plants, nutrient concentrations, biomass accumulation, harvest indexes, N uptake, N fertilizer efficiencies, and grain component data were recorded.

Grain harvest was conducted with a Case IH 7230 (CNH Industrial, Racine, WI) to estimate harvest moisture and grain yield. In 2017, the center 8 rows of each 24-row plot (rows 9-16) were harvested. In 2018, the center 8 rows of each 12-row planting pass (rows 3-10 and 15-22) were harvested for all treatments besides injection applications. For injection applications, 8 rows from the center of each plot (rows 9-16) were harvested because of the coulter-injected N application width constraints (just 16 of 24 rows). All grain yield and harvest moisture values were extracted from an AFS Pro 700 (CNH Industrial, Racine, WI) calibrated yield monitor where the data was cleaned to eliminate plot ends and non-representative areas (e.g. ponding, planter skips, etc.).

The derivation of N efficiency metrics such as NUE, NRE, and NIE are shown in Eq. [1 to 3] below.

$$\text{Eq. [1]} \quad \text{NUE} = \frac{\text{GY}_{\text{Nfert}} - \text{GY}_{\text{Nunfert}}}{\Delta_{\text{N applied}}}$$

$$\text{Eq. [2]} \quad \text{NRE} = \frac{\text{TNU}_{\text{Nfert}} - \text{TNU}_{\text{Nunfert}}}{\Delta_{\text{N applied}}}$$

$$\text{Eq. [3]} \quad \text{NIE} = \frac{\text{GY}_{\text{Nfert}} - \text{GY}_{\text{Nunfert}}}{\text{TNU}_{\text{Nfert}} - \text{TNU}_{\text{Nunfert}}}$$

In the equations above, GY_{Nfert} is the grain yield of plots receiving N, $GY_{Nunfert}$ is the grain yield of starter fertilized control plots, TNU_{Nfert} is the total N uptake of N fertilized plots, $TNU_{Nunfert}$ is the total N uptake in control plots that only received starter fertilizer, and $\Delta_{Napplied}$ is the difference in fertilizer rate from the N fertilized plot and the zero/low fertilized plot.

3.4 Statistical Analysis

Statistical analysis was conducted using SAS 9.4 (SAS Institute, Cary NC). Homogeneity of variance between years was met as most variables displayed a p-value >0.01 for year interactions

(Carmer et al., 1969); the latter allowed most parameters for years 2017 and 2018 to be combined for analysis. As hybrids did not remain consistent, when a treatment by year interaction occurred we cannot separate whether the interaction as due to year, hybrid, or a combination of the two. All variables were combined except SPAD, NUE, NRE, NIE, NHI, and grain yield. SPAD analysis was separated for 2017 and 2018 due to the timing of measurements not being similar. NRE, NIE, and grain yield were separated due to treatment by year interactions. Because of the latter, NUE and NHI parameters were separated for comparison among similar variables. Analysis of variance was conducted using the mixed procedure PROC GLIMMIX with mean separation being performed with an LSMEANS statement. In addition to individual treatment separations, an analysis of variance was conducted with PROC GLIMMIX as a two-by-two factorial that included placement treatments of streaming (V5_str and V12_str) versus injection (V5_inj and V12_inj), and timing treatments of V5 (V5_str and V5_inj) versus V12 (V12_str and V12_inj) with mean separation using LSMEANS. This method was selected as determining interactions between fixed effects cannot be implemented into a main effects contrast analysis (Littell et al., 2006). For each analysis, treatment, placement, and timing were considered fixed effects. Block was treated as nested within year as a random effect. An α <0.05 was used to determine if a difference was significant for a treatment, placement, or timing effect.

3.5 Results

3.5.1 Weather

Individual growing season precipitation, mean temperature, and cumulative growing degree days (GDD_c; base 10°C) were recorded from nearby weather stations (Table 3.2). The vegetative growth period (May, June, July) received 27.1mm more precipitation in 2017 and 63.4mm less precipitation in 2018 when compared to the 30-year mean. The grain-filling period (Aug. and Sept.) received 112mm less precipitation in 2017 and 16.8mm more precipitation in 2018 compared to the 30-year mean. Overall, the mean growing season (May to Sept.) precipitation was 22% and 16% below the 30-year mean for 2017 and 2018, respectively. Temperatures aligned with GDD_c and were near normal in 2017. The 2018 growing season experienced 224 more GDD_c than the 30-year mean with the vegetative and reproductive growth periods accumulating 133 and 92 more GDD_c than the 30-year mean, respectively (Table 3.2).

Table 3.2. Cumulative precipitation, mean temperature, and cumulative growing degree days (GDD_c; base 10°C) for each month of the May-September growing season in 2017, 2018, and the historic 30-year mean (30-year; 1988-2017) located near La Crosse, Indiana at the Mary S. Rice farm.

	Precipitation (mm)			Mean Temperature (°C)			Growing Degree Days (GDD_c)		
Month	2017	2018	30-year	2017	2018	30-year	2017	2018	30-year
May	126.0	119.0	106.3	13.6	19.2	15.3	170.6	290.8	204.1
June	71.0	99.1	120.7	20.9	21.7	20.6	330.6	349.4	314.7
July	166.6	55.0	109.5	22.2	22.3	22.2	381.4	379.2	367.9
August	55.8	142.7	119.0	19.5	22.3	21.1	301.4	381.9	337.6
September	34.0	75.9	82.8	17.7	19.2	17.3	254.4	285.8	238.5
5-Month Total	**453.4**	**491.7**	**583.3**	**18.78**	**20.94**	**19.3**	**1,438.4**	**1,687.1**	**1,462.8**

Days until 10mm of precipitation within 48 hours following each N application were recorded for AP, V5, V8, and V12 timings each year. In 2017, at least 10mm fell within 48 hours of each N application (Fig. 3.1a). In 2018, 10mm of precipitation was received for AP, V5, V8, and V12 timings at 3, 8, 7, and 3 days following N application, respectively (Fig. 3.1b). According to Fox and Hoffman (1981) and Fox et al. (1986) for surface applications of N, we would expect near zero volatilization losses for all application timings in 2017. Volatilization loss after the at-plant application in 2018 was possible, but potentially reduced as 14mm of precipitation was recorded between the second and third day after application. The V5 timing in 2018 may have had moderate gaseous N losses before 10mm was recorded between days 7 and 8 after application. Slight to moderate volatilization could have occurred with V8_urea in 2018 as very little precipitation fell for 1 week after application. However, the urea was treated with Agrotain, which was likely effective at limiting volatilization until a single precipitation event of 31mm incorporated the urea 7 days after application. Of potentially more importance to corn N uptake, the 2018 rainfall delays after surface N placement at the V5 and V8 placements may have delayed mineral N availability to corn roots. The V12 N application was preceded and followed by a short dry period likely leading to minor losses. On the day of application 5mm was recorded and a 12mm precipitation event occurred 3 days later. Spackman et al. (2019) found timely and well-distributed rainfall was necessary for surface applied split N to be effective over at-plant or pre-plant applications.

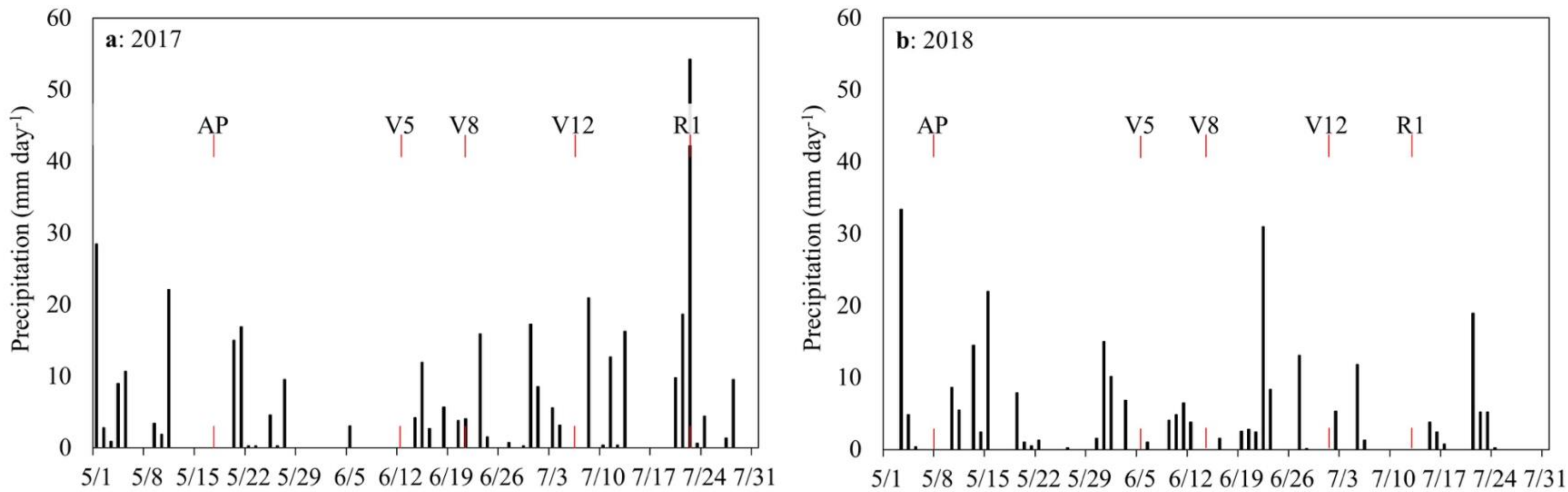

Figure 3.1. Daily precipitation (mm day$_{-1}$) from May-July with denoted at-plant (AP), V5, V8, and V12 timed N applications as well as flowering (R1) for 2017 (a) and 2018 (b).

3.5.2 Earleaf Nutrient Concentrations at Flowering

Significant N treatment impacts on earleaf N, S, Zn, and Cu were observed, but not for P or K concentrations (Table 3.3). Earleaf N% was highest with treatments receiving ≥202 kg N ha^{-1} which were greater than the Zero while V5_str which resulted in N concentration gains of 0.90% relative to AP_112. Earleaf S% was highest for all non-Zero treatments while AP_224, V5_str, and V8_urea treatments were 0.04% greater than the Zero treatment. The greatest Zn concentrations were achieved by non-Zero treatments while AP_224, V5_str, V5_inj, and V8_urea treatments were greater than the Zero treatment by ~5.4%. Similarly, earleaf Cu concentrations were highest with non-Zero treatments as AP_224, V5_str, and V5_inj treatments were significantly higher than the Zero treatment. The greatest concentrations of earleaf nutrients tended to occur following an earlier application of N either at-plant or at the V5 growth stage. This was reinforced in the timing analysis where V5 N applications proved superior to V12 timed applications for earleaf N and Zn concentrations (Table 3.3). However, earleaf P, K, S, and Cu concentrations did not statistically improve with an early N application timing.

Tri-state Fertilizer Recommendations (Vitosh et al., 1995) recommended earleaf concentrations for N, P, K, and S are between 2.90-3.50%, 0.30-0.50%, 1.91-2.50%, and 0.16-0.50%, respectively. Zn and Cu concentrations are recommended to be between 20-70 and 6-20 (mg kg^{-1}), respectively. None of our treatments met the suggested N and Zn thresholds. Only the Zero treatment failed to meet P and Cu standards at 0.27% and 5.00 mg kg^{-1}, respectively. Earleaf K concentrations were regarded as sufficient (ranging from 2.06-2.46%). Sulfur was below the recommended concentrations for the Zero and V12_str treatments while all other treatments were quite low at 0.16-0.17%, which reflects the minimum recommended S%. While S% was low, overall low N% resulted in the N:S ratio was near the recommended 15:1 (N:S) ratio (Reneau, 1983).

Table 3.3. Flowering (R1) earleaf concentrations for N, P, K, S, Zn, and Cu averaged across years (2017 and 2018) and post R1 SPAD for each year independently as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

		Flowering (R1) Earleaf Nutrient Concentrations						SPAD		
Individual	Total N	N	P	K	S	Zn	Cu	(R4)	(R2)	(R5)
Treatment†	(kg N ha^{-1})	(%)				(mg kg^{-1})		8/23/17	7/27/18	8/31/18
Zero	26	1.90 **c**	0.27	2.06	0.13 **b**	10.6 **b**	5.0 **b**	48.8 **ab**	41.5 **b**	12.5 **c**
AP_112	112	2.40 **b**	0.33	2.31	0.16 **ab**	13.9 **ab**	6.9 **ab**	48.4 **b**	55.9 **a**	30.4 **b**
AP_224	224	2.75 **ab**	0.37	2.43	0.17 **a**	16.4 **a**	7.9 **a**	54.1 **a**	58.8 **a**	48.0 **a**
V5_str	202	2.80 **a**	0.37	2.42	0.17 **a**	15.8 **a**	7.9 **a**	52.8 **ab**	59.6 **a**	48.3 **a**
V5_inj	202	2.70 **ab**	0.37	2.35	0.16 **ab**	15.9 **a**	7.7 **a**	52.3 **ab**	58.4 **a**	41.4 **ab**
V8_urea	202	2.75 **ab**	0.36	2.46	0.17 **a**	15.8 **a**	7.4 **ab**	52.2 **ab**	60.4 **a**	42.7 **a**
V12_str	202	2.65 **ab**	0.34	2.40	0.15 **ab**	14.0 **ab**	7.0 **ab**	52.1 **ab**	59.7 **a**	46.1 **a**
V12_inj	202	2.55 **ab**	0.33	2.24	0.16 **ab**	14.0 **ab**	7.1 **ab**	51.6 **ab**	59.7 **a**	42.9 **a**
Sidedress UAN Treatment Groups		Level of Significance Pr > F								
Placement‡		ns¶	ns	ns	ns	ns	ns	ns	ns	ns
Timing§		*(V5)	ns	ns	ns	*(V5)	ns	ns	ns	ns
Placement x Timing		ns	ns	ns	ns	ns	ns	ns	ns	ns

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha^{-1} as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha^{-1} (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).

‡Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)

§Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)

¶ns, nonsignificant at p<0.05 probability level

*Significant at p<0.05 probability level

3.5.3 SPAD

A SPAD meter estimates chlorophyll content in the leaves by recording leaf spectral transmittance (Fox and Walthall, 2008) which can be used to predict leaf N concentration as SPAD and leaf N concentration are highly correlated (Markwell et al., 1995). SPAD measurements were taken post R1 in each growing season. At R4, AP_224 had a leaf SPAD value of 5.7 units greater than AP_112 in 2017 (Table 3.3). By R2 in 2018, all treatments with ≥112 kg N ha^{-1} had a mean SPAD value of 58.9 versus a SPAD value of 41.5 for the Zero (Table 3.3). By R5, leaf senescence from N stressed plants had progressed up to the earleaves in the Zero and AP_112 treatments. All treatments were significantly greater than the Zero which only had a SPAD value of 12.5. The AP_112 treatment showed some N stress with a corresponding SPAD value of 30.4, which was significantly lower than most other treatments receiving sidedress N. Highest SPAD at R5 was observed in the V5_str treatment (48.3), indicating high chlorophyll contents in earleaves late into the grain-filling period (Table 3.3).

3.5.4 Physiological Maturity N Concentrations

All full N rate treatments had similar stover and grain N% at maturity (Table 3.4). Grain N% was influenced most by total N rate with the Zero having the lowest grain N at 0.73%, followed by AP_112 at 0.92%, and full N rate treatments averaging 1.04% (Table 3.4). However, the V5 applications resulted in slightly higher grain N% (1.06%) than V12 (1.02%) applications with grain N means of 1.06% and 1.02%, respectively (Table 3.4). All treatments with a total N rate ≥112 kg ha^{-1} were not different among each other in stover N. The AP_224, V5_str, V5_inj, and V12_str treatments had a significantly higher stover N averaging ~0.81% versus the Zero at 0.56% (Table 3.4).

Table 3.4. Physiological maturity (R6) plant N concentrations for stover, cob, and grain averaged across years (2017 and 2018) as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

		Maturity (R6) N Concentrations		
Individual Treatment†	Total N (kg N ha-1)	Stover	Cob†	Grain
			(%)	
Zero	26	0.56 **b**	0.56	0.73 **c**
AP_112	112	0.66 **ab**	0.69	0.92 **b**
AP_224	224	0.79 **a**	0.57	1.04 **a**
V5_str	202	0.85 **a**	0.64	1.06 **a**
V5_inj	202	0.79 **a**	0.66	1.06 **a**
V8_urea	202	0.78 **ab**	0.66	1.04 **a**
V12_str	202	0.81 **a**	0.75	1.00 **a**
V12_inj	202	0.75 **ab**	0.64	1.04 **a**
Sidedress UAN Treatment Groups			Level of Significance Pr > F	
Placement§		ns#	--	ns
Timing¶		ns	--	*(V5)
Placement x Timing		ns	--	ns

†Not statistically analyzed, only one rep of data
‡Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha-1 as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha-1 (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).
§Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)
¶Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)
#ns, nonsignificant at p<0.05 probability level
*Significant at p<0.05 probability level

3.5.5 Grain Yield and Yield Components

Grain yields averaged across treatments receiving a total N rate of ≥202 kg ha-1 was 14.01 Mg ha-1 in 2017 and ~11.5 Mg ha-1 in 2018 (Table 3.5). The Zero treatment produced just 7.54 and 4.35 Mg ha-1 of grain in 2017 and 2018, respectively, which was significantly lower than all other treatments each year. Grain yield in 2017 was highest with AP_224, V5_str, V5_inj, V8_urea, and V12_str treatments which were superior to both AP_112 and the Zero treatments (Table 3.5). In 2017, both V12_str and AP_224 yielded ~0.91 Mg ha-1 more than V12_inj. A placement difference in 2017 indicated streaming yielded more than injection methods by 0.64 Mg ha-1. The placement difference was primarily due to the significantly higher yield for streaming versus injection at the late (V12) timing (Table 3.5). In 2018, the full N rate treatments yielded an average of 2.20 Mg ha^{-1} more than the AP_112. Statistical differences were not found between full N rate treatments, N placement, or N timing in 2018 (Table 3.5). Except for V12_inj in 2017, there was no yield advantage between split application methods and a single at-plant application, even though the AP_224 treatment received 22 kg ha^{-1} more N.

Kernel number and kernel weight are reported as the mean of both years (Table 3.5) as each year responded similarly. Grain yield was primarily driven by individual kernel weights which showed a positive relationship to increasing N from Zero to AP_112 to full N rate treatments. Kernel weights were similar among full N rate treatments, and collectively improved kernel weight by a mean of 46 mg $kernel^{-1}$ and 99 mg $kernel^{-1}$ over AP_112 and Zero, respectively (Table 3.5). Nitrogen placement and timing treatment groups were not significant for kernel weight (Table 3.5). In terms of kernel number, treatments ≥112 kg N ha^{-1} had ~534 kernels pl^{-1}, which were significantly greater than Zero at 406 kernels pl^{-1}. Harvest moisture remained consistent across treatments, placement, and timing with a range of 16.2-16.4% H_2O. All treatments with an N rate ≥112 kg N ha^{-1} had a mean harvest index (HI) of ~58.6% which was significantly greater than the Zero at 50.9% (averaged across growing seasons). Average HI was never significantly affected by N placement and timing treatments using the same common total 202 kg N/ha rate.

Table 3.5. Kernel number plant^{-1}, mean individual kernel weight (0% H_2O), harvest moisture, and harvest index averaged across years (2017 and 2018) and grain yield (Mg ha^{-1} at 15.5% H_2O) reported for each year independently as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

		Mean of 2017 and 2018				2017	2018
Individual	Total N	Kernel Number	Kernel Weight	Harvest Moisture	Harvest Index	Grain Yield	
Treatment†	(kg N ha^{-1})	(kernels plant^{-1})	(mg kernel^{-1})	(%)	(%)	———(Mg ha^{-1})———	
Zero	26	406 **b**	216 **c**	16.2	50.9 **b**	7.54 **d**	4.35 **c**
AP_112	112	506 **a**	269 **b**	16.2	56.5 **a**	11.93 **c**	9.25 **b**
AP_224	224	537 **a**	319 **a**	16.4	58.9 **a**	14.39 **a**	11.72 **a**
V5_str	202	529 **a**	319 **a**	16.3	58.2 **a**	14.25 **ab**	11.59 **a**
V5_inj	202	551 **a**	311 **a**	16.4	59.8 **a**	13.89 **ab**	11.25 **a**
V8_urea	202	532 **a**	312 **a**	16.3	59.1 **a**	13.64 **ab**	11.52 **a**
V12_str	202	549 **a**	316 **a**	16.3	58.9 **a**	14.40 **a**	11.25 **a**
V12_inj	202	537 **a**	312 **a**	16.3	58.9 **a**	13.49 **b**	11.38 **a**
Sidedress UAN Treatment Groups		Level of Significance Pr > F					
Placement‡		ns¶	ns	ns	ns	*(str)	ns
Timing§		ns	ns	ns	ns	ns	ns
Placement x Timing		ns	ns	ns	ns	ns	ns

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha^{-1} as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha^{-1} (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).

‡Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)

§Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)

¶ns, nonsignificant at p<0.05 probability level

*Significant at p<0.05 probability level

3.5.6 Biomass and N Uptake Accumulation

Biomass accumulation generally improved for stover, cob, and grain when the total N rate applied exceeded the Zero and AP_112 treatments (Fig. 3.2). Treatments ≥112 kg N ha^{-1} produced an average of 1,866 kg ha^{-1} more stover biomass than the Zero. Cob biomass was similar for all rates ≥202 kg N ha^{-1}. Cob biomass for the AP_224 and V8_urea treatments was significantly greater than the AP_112 treatment. Injection treatments, irrespective of N timing, had similar biomass totals to AP_112 in grain and total biomass resulting in the only full N rate treatments responding significantly similar to AP_112. The AP_224, V5_str, V8_urea, and V12_str treatments produced significantly greater grain and plant biomass than AP_112. The numerically greatest total biomass was achieved by V12_str, but all full N rate treatments were similar for stover, cob, grain, or whole-plant biomass. Sidedress UAN treatment group analysis indicated no significant differences for any plant biomass accumulation at maturity (Supplemental Information Table 3.7).

Total N rate was the driving factor for treatment differences in grain and whole plant N uptake (Fig. 3.3). Both grain and total N uptake increased as N rate increased from Zero to AP_112, and again from AP_112 to full N rate treatments. However, among full N rate treatments, there were no significant differences in stover, cob, grain, or total N uptake (Fig. 3.3). For stover N uptake, full N rate treatments were greater than the Zero, but similar to the AP_112 treatment. The Zero accumulated the least amount of aboveground N at just 75.7 kg ha^{-1} (Supplemental Information Table 3.8). Stover, cob, grain, and whole plant N uptakes were not altered by sidedress UAN treatment groups (Supplemental Information Table 3.8)

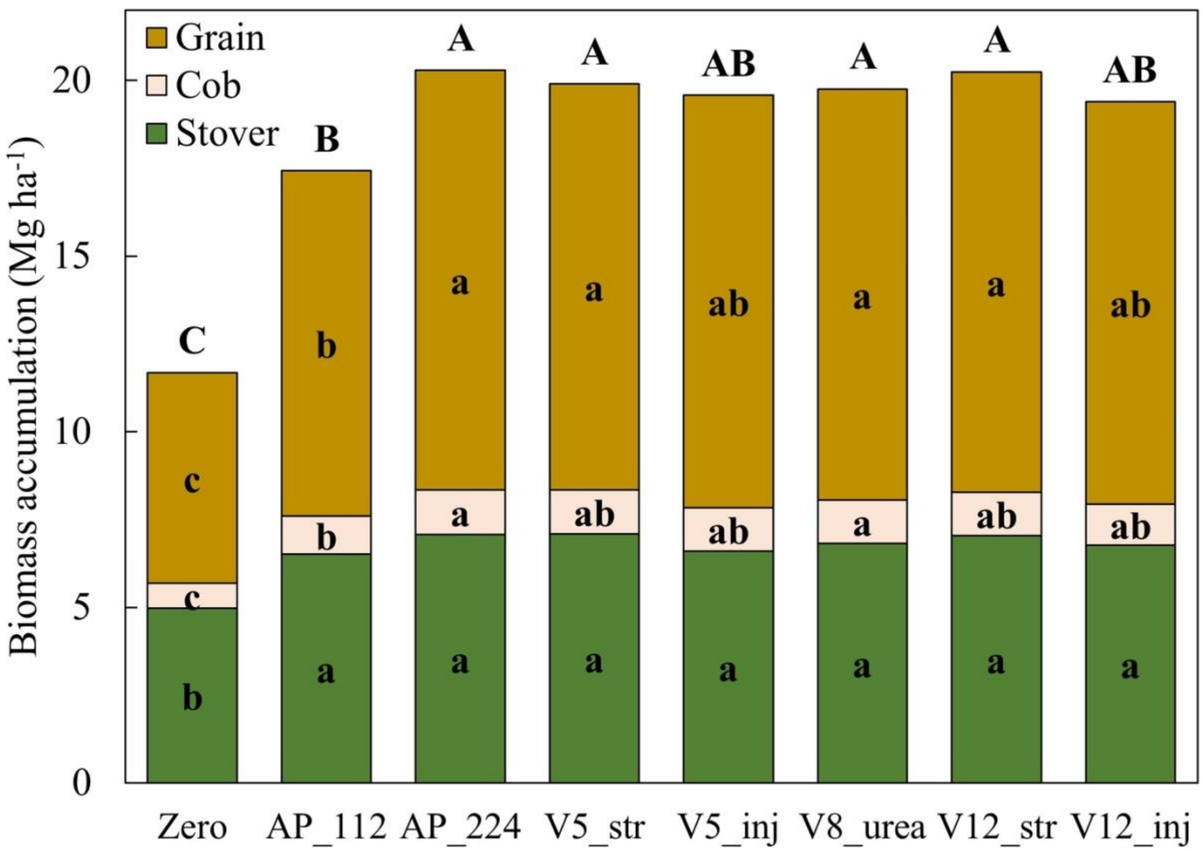

Figure 3.2. Physiological Maturity (R6) biomass accumulation for stover, cob, grain, and total averaged across years (2017 and 2018) as affected by treatments; N application treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha-1 as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha-1 (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea). Different letters indicate a significant difference at p-value <0.05.

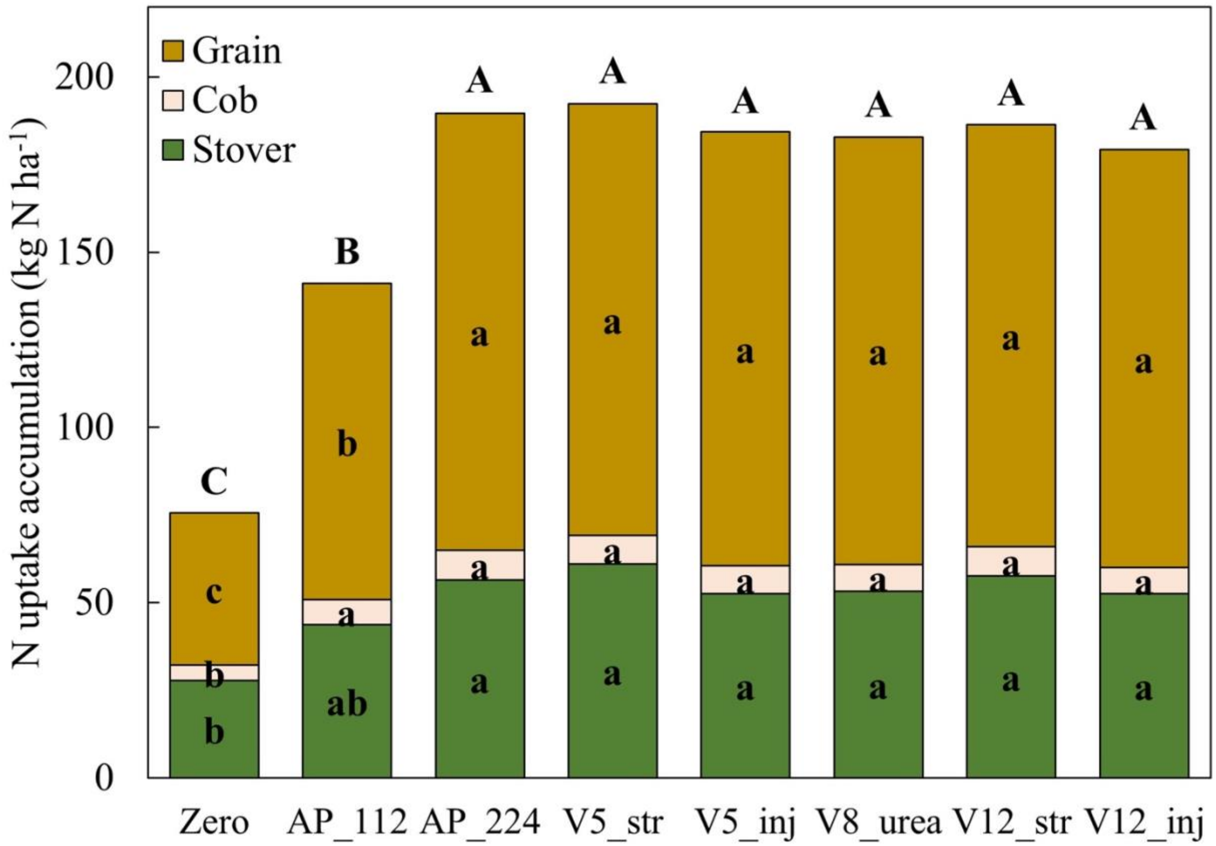

Figure 3.3. Physiological Maturity (R6) N uptake accumulation for stover, cob, grain, and total averaged across years (2017 and 2018) as affected by treatments; N application treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha^{-1} as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha^{-1} (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea). Different letters indicate a significant difference at p-value <0.05.

3.5.7 N Fertilizer Efficiencies and N Harvest Index

Nitrogen harvest index (NHI) indicates how efficient plants were at relocating vegetative N supplies to the grain (Fageria, 2014). Full N rate treatments (≥202 kg N ha^{-1}) had a mean NHI of ~71.9 and 61.1% for 2017 and 2018, respectively, indicating that about two-thirds of total plant N at maturity was present in the grain (Table 3.6). However, NHI was not influenced by individual treatments or the placement and timing group treatments for split-sidedress applications (Table 3.6).

Overall NUE for each growing season was highest with AP_112 (at 57.0 and 44.3 kg kg^{-1} for 2017 and 2018, respectively) as expected (Table 3.6). In 2017, NUE was higher with AP_112 compared to all other treatments, while in 2018 the AP_112 had higher NUE than all other treatments but V5_str. In 2017, surface streaming UAN applications improved NUE by an average of 3.95 kg kg^{-1} over injection methods.

The 2017 results for NRE and NIE indicate no treatment differences for NRE and a significant treatment difference for NIE. AP_112 had the highest NIE at 93.3 kg kg^{-1} which was significantly above all other treatments except AP_224 with a NIE of 70.8 kg kg^{-1} (Table 3.6). Nitrogen recovery efficiency was not responsive to treatments in 2017, possibly due to overall low means (~57.7%) in relation to 2018 (~68.1%) (Table 3.6). Sidedress UAN treatment groups didn't indicate significant differences for NRE and NIE in 2017 (Table 3.6).

The 2018 growing season had the inverse effects on NRE and NIE when compared to 2017 as treatment differences in NIE were insignificant while NRE had significant treatment separations in 2018. AP_112 had the highest NRE in 2018 at 92.4%, which was significantly greater than all other treatments except V5_str with a NRE of 72.1% (Table 3.6). The average NIE in 2018 declined from 68.0 kg kg^{-1} the previous year to 44.9 kg kg^{-1} and, furthermore, treatment separations were not apparent. Placement and N application timing was not influential on NRE or NIE in 2018.

Table 3.6. Physiological Maturity (R6) N use efficiency (NUE), N internal efficiency (NIE), N recovery efficiency (NRE), and N harvest index (NHI) reported for each year independently as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

Individual Treatment†	Total N (kg N ha^{-1})	NUE 2017	NUE 2018	NIE 2017	NIE 2018	NRE 2017	NRE 2018	NHI 2017	NHI 2018
		(kg kg^{-1})				(%)			
Zero	26	--	--	--	--	--	--	64.4	51.5
AP_112	112	57.0 **a**	44.3 **a**	93.3 **a**	46.6	55.5	92.4 **a**	71.5	59.0
AP_224	224	38.7 **b**	28.4 **b**	70.8 **ab**	45.4	49.9	63.6 **b**	71.0	62.1
V5_str	202	42.7 **b**	29.8 **ab**	65.5 **b**	42.2	58.9	72.1 **ab**	70.0	59.8
V5_inj	202	40.5 **b**	26.7 **b**	59.6 **b**	43.4	60.5	62.7 **b**	73.0	62.6
V8_urea	202	38.8 **b**	29.1 **b**	59.1 **b**	46.5	59.2	62.2 **b**	72.1	62.3
V12_str	202	43.6 **b**	27.4 **b**	59.7 **b**	47.2	66.1	60.3 **b**	70.1	59.9
V12_inj	202	37.9 **b**	26.9 **b**	68.2 **b**	43.0	53.5	63.3 **b**	75.4	59.8
Sidedress UAN Treatment Groups		Level of Significance Pr > F							
Placement‡		*(str)	ns	ns	ns	ns	ns	ns	ns
Timing§		ns¶	ns	ns	ns	ns	ns	ns	ns
Placement x Timing		ns	ns	ns	ns	ns	ns	ns	ns

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha^{-1} as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha^{-1} (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).

‡Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)

§Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)

¶ns, nonsignificant at p<0.05 probability level

*Significant at p<0.05 probability level

3.6 Discussion

While sidedress timing and placement strategies have been extensively researched, the comparison of multiple placement methods at both early and late sidedress has not. Although the N rate impact was dominant in both years, the timing of full-rate N applications from at-plant to split-sidedress as late as V12 did not influence grain yields. Our research results agree with Welch et al. (1971), Killorn and Zourarakis (1992), Jokela and Randall (1997), Randall et al. (2003), Randall and Schmitt (2004), Abbasi et al. (2012), Jaynes (2013), and Spackman et al. (2019) for situations where growing-season precipitation levels were near normal. Both individual treatments and sidedress UAN treatment groups responded similarly among sidedress timings (V5 and V12) for grain yield and yield components in both 2017 and 2018. Surface streaming UAN was superior to coulter injection for grain yield in 2017 (Y-Drop™ at both V5 and V12) while no differences were detected in 2018 (V5: 5-band surface streamed, V12: Y-Drop™). These differences in response between the two years agrees with inconsistency of responses often found in the literature (e.g., Woodley et al., 2017 versus Maddux et al., 1991).

The superior N fertilizer efficiencies (NUE, NRE, and NIE) following AP_112 was anticipated as lower N rates allow for better plant utilization because fertilizer loss is minimized (Russelle et al., 1981). The lack of sidedress timing differences between V5 and V12 on total N uptake agrees with Mueller and Vyn (2018) who found late N applications yielded similarly to early sidedress applications. Kovács et al. (2015) showed a positive response to pre-plant N timings (with NH_3) improving both total N uptake and yield while we observed no differences between 100% at-plant and split sidedress at V5, V8 or V12.

Earleaf nutrient concentrations can be used to monitor plant health and even predict grain yield. For example, Kovács and Vyn (2017) found earleaf N, P, S, and Cu concentrations at the R1 stage explained >50% of the total variation in grain yield and whole plant biomass accumulation. The V5 timed N applications were superior in earleaf and grain N% indicating that plants may have been better able to recover and remobilize N to the grain with earlier applications, although timing was not significant in final N fertilizer efficiencies, total N uptake, or grain yield.

Additionally, V8_urea's response was similar to corn responses with sidedress timing (V5 and V12) and placement (streaming and injection) in all measured variables despite having N applied ~10 days later than V5 and ~15 days before V12 applications. We might expect V8_urea to produce greater NRE and grain yields as Drury et al. (2017) found N loss reduced when urease and/or nitrification inhibitors were utilized on both urea and UAN sources, although a urea source with a urease inhibitor was included in our comparison.

The lack of N treatment responses in total biomass in our study agreed with Schröder (1999), who concluded that biomass accumulation was not influenced by split N timings. Generally, split N applications are better at recovering N compared to at-plant applications when vegetative stage precipitation is above normal (Jokela and Randall, 1989; Randall et al., 2003; Randall and Schmitt, 2004; Gehl et al., 2005). Vegetative stage (May to July) precipitation was recorded at 27.1mm greater and 63.4mm less when compared to the 30-year mean in 2017 and 2018, respectively. It is possible that our near-average or below-average precipitation did not promote enough N loss to favor the split N approach over at-plant. Although AP_224 received 22 kg ha^{-1} more N compared to split-sidedress applications, near-identical yields may not economically support the extra cost of custom in-season N applications when compared to the cost of a single at-plant application at a slightly higher total N rate.

With precipitation being a primary factor in differing at-plant versus sidedress N applications, we would expect our split N treatments to respond similarly in yield to our AP_224 when growing season precipitation is near normal. However, limited precipitation after the V5 and V8 applications in 2018 combined with above normal temperatures could have reduced potential N uptake because of delayed or reduced soil mineral N availability to corn roots. In a timelier, or overall higher, precipitation environment more grain yield and N fertilizer efficiency differences may have occurred with split N approaches.

3.7 Conclusions

We set out to compare at-plant, traditional sidedress, and late sidedress timings using modern equipment with alternate N placement technologies for corn in a field-scale, rain-fed environment. Although not statistically different in final yields, split N applications utilized N resources more efficiently, minimized plant N stress, and produced similar yields to single-time at-plant applications that received 22 kg ha^{-1} more N.

There was limited evidence that either V5 or V12 sidedress timing was superior to the other in grain yield during our two-year trial. The latter suggests N can be applied up to V12 without negative growth or yield consequences when in-season precipitation is near normal, and when >50% of the total N is supplied near planting. The only sidedress placement advantage was observed in

2017 when a 640 kg ha^{-1} grain yield improvement for streaming applications occurred (driven mostly by a 910 kg ha^{-1} increase for V12_str over V12_inj).

Our study results suggest that there is potential for early split N applications to improve earleaf N and Zn concentrations at flowering while also improving grain N% at maturity. Earleaf N and Zn concentration improvement occurred only at V5 N applications and irrespective of surface or subsurface placements. However, surface streaming applications seemed to slightly improve earleaf S% and total biomass at both V5 and V12 timings (as indicated by their improvement over the AP_112 treatment that the V5_inj and V12_inj treatments failed to achieve). Sidedress UAN treatment group comparison between streaming and injection methods across V5 and V12 timings found surface-streaming methods increased grain yield as well as NUE in 2017 (Y-Drop™ utilized in each application).

In this research, monthly precipitation was notably below historic means in June, Aug., and Sept. 2017 and during July 2018. Growing season precipitation for both years was 22 to 16% below the 30-year mean. Previous research suggests similarity between 100% at-plant and split N applications in corn N uptake, NRE, and grain yield when in-season precipitation was not so excessive as to promote high N losses. In an environment that experienced more vegetative stage precipitation (either artificially or naturally), we would expect an N uptake, NRE, or grain yield advantage for split N applications. Further research investigating sidedress application methods and timings should be conducted to determine the influence that various environments have on these and other split-sidedress placement and timing methods.

3.8 Acknowledgments

A special thank you to Dr. Tony Vyn's cropping system crew during the 2017 and 2018 growing seasons for their careful and hard work both in collection and processing samples to acquire this dataset. Also, thank you to John Deere for their financial support of this project and the Indiana Corn Marketing Council for additional support in 2018-2019 via a 12-month graduate scholarship.

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3.11 Supplemental Information

Supplemental Information Table 3.7. Physiological Maturity (R6) biomass accumulation for stover, cob, grain, and total averaged across years (2017 and 2018) as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

		Biomass Accumulation			
Individual Treatment†	Total N (kg N ha^{-1})	Stover	Cob	Grain	Total
		(kg ha^{-1})			
Zero	26	4,975 **b**	712 **c**	6,072 **c**	11,674 **c**
AP_112	112	6,508 **a**	1,082 **b**	9,859 **b**	17,434 **b**
AP_224	224	7,067 **a**	1,278 **a**	11,810 **a**	20,292 **a**
V5_str	202	7,098 **a**	1,237 **ab**	12,164 **a**	19,908 **a**
V5_inj	202	6,600 **a**	1,230 **ab**	11,550 **ab**	19,572 **ab**
V8_urea	202	6,812 **a**	1,247 **a**	12,271 **a**	19,742 **a**
V12_str	202	7,039 **a**	1,231 **ab**	11,612 **a**	20,238 **a**
V12_inj	202	6,764 **a**	1,175 **ab**	11,551 **ab**	19,451 **ab**
Sidedress UAN Treatment Groups		Level of Significance Pr > F			
Placement‡		ns¶	ns	ns	ns
Timing§		ns	ns	ns	ns
Placement x Timing		ns	ns	ns	ns

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha^{-1} as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha^{-1} (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).
‡Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)
§Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)
¶ns, nonsignificant at p<0.05 probability level

Supplemental Information Table 3.8. Physiological Maturity (R6) N accumulation for stover, cob, grain, and total averaged across years (2017 and 2018) as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

		Maturity (R6) Nitrogen Accumulation			
Individual Treatment†	Total N (kg N ha-1)	Stover	Cob	Grain	Total
		(kg N ha-1)			
Zero	26	27.8 **b**	4.4 **b**	43.5 **c**	75.7 **c**
AP_112	112	43.7 **ab**	7.1 **a**	90.2 **b**	141.1 **b**
AP_224	224	56.5 **a**	8.4 **a**	124.8 **a**	189.7 **a**
V5_str	202	61.1 **a**	8.1 **a**	123.1 **a**	192.3 **a**
V5_inj	202	52.6 **a**	7.9 **a**	123.8 **a**	184.3 **a**
V8_urea	202	53.2 **a**	7.8 **a**	121.9 **a**	182.8 **a**
V12_str	202	57.7 **a**	8.3 **a**	120.4 **a**	186.3 **a**
V12_inj	202	52.5 **a**	7.4 **a**	119.2 **a**	179.2 **a**
Sidedress UAN Treatment Groups		Level of Significance Pr > F			
Placement‡		ns¶	ns	ns	ns
Timing§		ns	ns	ns	ns
Placement x Timing		ns	ns	ns	ns

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha-1 as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha-1 (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).

‡Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)

§Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)

¶ns, nonsignificant at p<0.05 probability level

CHAPTER 4. GENERAL DISCUSSION

4.1 Research Summary and Contributions to Science

Research presented in this thesis (from experiments conducted in 2017 and 2018) explores emerging N management approaches to optimize efficiency in farmer operations and nutrient use. While extensive research exists covering at-plant and sidedress N systems in corn, the use of modern technology options included in replicated field-scale trials is relatively rare. Nitrogen is the most widely applied nutrient globally and is a leading pollutant to the atmosphere and water. Government regulations concerning its use may be avoidable if the adoption of new technologies or redesigned N management practices can assist in a reduction in negative environmental impacts. One of the best mechanisms to prevent N losses in corn production is to achieve higher N recovery efficiencies (NRE) of the fertilizer that is applied.

Chapter 1, in a brief literature review, addresses the 4R’s (4R’s: right source, right rate, right time, and right place) of nutrient management, with specific discussions of how each R Influences N management and its consequences for fertilizer recovery and grain yield. Management practices employed and published in the literature vary widely across the spectrum of potential 4R practices. Climate and weather have major impacts on fertilizer losses. Due to the large influence of such outside forces, we have learned that environmentally sound practices such as in-season N applications may not always provide greater fertilizer recovery or produce comparable corn grain yields to a single pre- or at-plant N application. Likewise, an increase in total plant N fertilizer recovery is not always accompanied by an increase in yield. Variable results from similar and contrasting geographies make generalizable conclusions difficult, and make new science-based recommendations to farmers even more difficult.

The focus of Chapter 2 was on determining and proving the effectiveness of high rate planter-applied N (a relatively new N management practice) in modern corn production systems. Furthermore, this experiment occurred in the context of a continuous corn cropping system and at overall N rates ~45 kg ha^{-1} less than the agronomic optimum (Camberato and Nielsen, 2019) to promote some N deficiency stress while not considerably compromising yields. With adequate soil moisture present in the silt loam soil at planting, moderate (101 kg N ha^{-1}) and high (202 kg N ha^{-1}) planter-banded N rates were proven effective as statistically similar yields were recorded for all

N rates in 2017, and yield was improved with the 101 kg N ha^{-1} rate over both 34 and 202 kg N ha^{-1} rates in 2018. At-plant N placement near the seed (i.e. 5cm from the seed row and 5cm from the soil surface), even at the high N rates, did not negatively influence grain yield in either growing season. However, in 2018 when comparing 5x5 and 10x5 banding, 10x5 banding resulted in slightly reduced grain yield. Similarly, when additional placements were included (i.e. distances of 13 or 20cm from the seed row at 5 or 10cm depths) yield was reduced when banding at 5x13 or 10x20 compared to 5x5 (averaged across 101 and 202 kg N ha^{-1} at-plant rates). Grain moisture at harvest was always lowest when banding 101 kg N ha^{-1} compared to at-plant banding of only 34 kg N ha^{-1}. Increased yield with planter-banded N at 101 kg ha^{-1} was achieved at placements that are relatable to most banded starter fertilizer placements. The grain yield improvement documented with the 101 kg N ha^{-1} rate in 2018 was accompanied by an NRE of 86.1%, well above our target of 70%. The overall high NRE's obtained in 2018 were presumably associated with below-optimum agronomic N rates (of just a total of 202 kg N ha^{-1} in a continuous corn cropping system favoring high N fertilizer uptake.

Although there's been considerable research conducted on the effects of sidedress N applications on both yield and NRE, continued experimentation (like that described in Chapter 3) is needed on late-split sidedress N timing and N placement, especially when employing modern N placement solutions. Utilizing modern application technology, such as the Y-Drop™ surface streaming approach, paired with high clearance applicators (i.e. Hagie) makes the research described in Chapter 3 relevant to farmers incorporating new technology and machines into their operations. Of the two years this trial was conducted, only in 2017 did streaming (i.e. Y-Drop™) improve grain yield compared to subsurface injection. The advantage for the streaming placement in 2017 was greatest at the late V12 timing where grain yield was increased by 0.91 Mg ha^{-1} (+6.7%) compared to the injection placement. In 2018, both injection and surface streaming applications yielded similarly. Nitrogen recovery efficiency was not influenced by N treatments, timing, or placement in 2017 with mean NRE's of 49.9 to 66.1%. In 2018, the AP_112 treatment recorded the highest NRE at 93.3%, but this was accompanied with a yield loss of ~2.2 Mg ha^{-1} (-19.2%) at the lower N rate compared to treatments receiving ≥202 kg N ha^{-1}. Only V5_str met our research program's NRE target of 70%, (statistically similar mean to AP_112) without suffering from a yield loss as AP_112 yielded 2.34 Mg ha^{-1} (-20.2%) less than V5_str. Results from Chapter 3 add value to the effects of the Y-Drop™ system in a field-scale setting where surface N applications always produced neutral to greater yields when compared to subsurface injection. Continued academic research of modern N application technologies is warranted due to the positive influence current and continued research can have on both farmer and crop consultant N management decisions.

Results in Chapter 3 indicate that in only one instance (i.e. the V12_inj treatment) was a late sidedress approach lower yielding than at-plant or V5 sidedress. As the literature reviewed in Chapter 1 and Chapter 3 indicates, negative yield results are typically not found with late-season N applications if >50% of the whole-season N rate is supplied near planting. Because there are few constraints to late-season N application, the implementation and further development of spectral sensing technology could allow for prescribed in-season applications that are based on in-field or remotely sensed responses. Currently, remote sensing consumes too much time from detecting a spectral difference and making an application before a negative yield consequence associated with N-deficient corn may already have occurred. Hopefully, with the addition of this research concluding minimal to no negative consequences for late-season N, more funding and research will be conducted to further advance optimum strategies for in-season N applications. Theoretically, in-season applications should reduce total N requirements and promote more in-season uptake to minimize our overall environmental impact.

4.2 Implications to Agriculture

Our field-scale trials allowed modern full-sized production equipment to be utilized, although the large plot sizes stretched funding as well as land resources. Our field-scale trials better reflect a real-world scenario than similar N rate applications made by hand. Having conducted each trial in a field-scale setting, the conclusions from this thesis should translate well to crop consultants and farmers.

Aside from our research conclusions, a possible outcome could be to help encourage the production of a next-generation John Deere ExactEmerge™ planter with capabilities to deliver 40 to 100% of a full N rate at the time of planting. Various factors and engineering solutions would be needed to not only deliver the high volume of fertilizer but manage the volume of liquid storage farmers in the U.S. Corn Belt need to cover the acreage and not cause excessive compaction or yield reductions. A new planter would also have to compete with capabilities in efficiency as modern planters are capable of speeds up to and even exceeding 16 km hr^{-1}. One economic incentive for higher at-plant N rates might be the additional reduction in harvest moisture we noticed each year when compared to a traditional starter rate. Growers who wish to minimize corn drying costs and reduce natural gas consumption might try increasing their at-plant N rates with next-generation planters. Finally, the ability to pair a ~50% planter banded N application to a common (V4 to V6) or late (≥V10) sidedress application reduces a pass across the field needed when utilizing a pre or at-plant (i.e. not simply a starter fertilizer) and sidedress split N approach.

While sandy loam soils in our sidedress trials are not dominant in Indiana, many farmers in both Indiana and the Midwest face the fertility management challenges associated with sandy soils. Even though groundbreaking conclusions were not made regarding sidedress placement or timing methods, surface-streaming was never at a disadvantage when compared to the widely accepted method of subsurface injection. Surface streaming allows for fast and relatively cost-effective applications with the simple modification of a standard liquid chemical applicator. These small modifications expand the possibility for farmers to apply N either later in the growing season, or at increased speeds, compared a typical pull-behind coulter injection toolbars.

Improved N management and utilization of N fertilizer in corn production is the long-term goal of continued research in this area. Our research group's target NRE is 70% when employing economically optimum N rates to maintain or improve upon current yield production. In Chapter 3 this goal was not met in 2017. However, in 2018 both AP_112 and V5_str exceeded the 70% threshold. However, AP_112 only achieved a yield of 9.25 Mg ha^{-1} compared to V5_str at 11.59 Mg ha^{-1}. In Chapter 2 NRE was only recorded in 2018, and for that season the true 50:50 split N approach between at-plant and V6 sidedress recorded an NRE of 86.1% at 13.18 Mg ha^{-1} (thus confirming that reaching or surpassing a 70% NRE at high yield levels is possible). In both experiments when our 70% goal NRE was met, a split N approach between at-planting (e.g. in Chapter 2 UAN was planter banded and in Chapter 3 the at-plant UAN was broadcast within 48 hours of planting) of ≥50% of the total N rate followed by an early (i.e. V5 to V6) sidedress. Although we learned about the influence timing has on NRE, there is also potential for N placement to influence NRE and yield. In Chapter 3, surface streaming (averaged across V5 and V12 timings) improved yield compared to subsurface injection in 2017. However, NRE was not influenced by placement in 2017. Chapter 2 told a different story, in that yield suffered when high rates of N was planter banded at 5x13 and 10x20 placements and that placement alternatives didn't influence NRE. To improve both NRE and/or yield this research suggests a split N approach between at-plant and early sidedress provides the greatest opportunity for success. However, additional or possibly more frequent success may be found with a 50:50 split N approach when sufficient at-plant N is readily available to promote early season growth and development (especially in continuous corn).

4.3 Limitations of Research

Both research trials have added new results to the scientific and agricultural community. Each experiment was "applied research" as our N management strategies could be implemented into a farmer's operation with relative ease and at a limited cost for a large modern farmer. However, even with a well thought out protocol and implementation of the research, each experiment faced limitations that prevented stronger conclusions.

Chapter 2 suffered greatly from an unbalanced design that forced the treatment selection to feature only 14 of the available 17 N rate by placement combinations. Although 14 treatments were included, the absence of the 34 kg N ha^{-1} rate at many of the placements resulted in just 6 treatments being included for much of the analyses. Our reduced treatment set was primarily driven by funding constraints as well as an overall lack of suitable farmland with sufficiently large fields at the ACRE research site to accomplish so many treatments (17 in 2017 and 19 in 2018) and still maintain an appropriate number of replications (4). A completely balanced design would have ideally involved 3 depths (0, 5, and 10cm) by 3 (5, 13, 20 cm) or 4 (5, 10, 15, 20 cm) placements at 3 N rates (34, 101, and 202 kg N ha^{-1}) totaling 27 or 36 treatments before adding a 100% sidedress control (included in 2017 and 2018, Appendix A. Chapter 2) or a zero N control (added in 2018). Because of this, our primary focus in the presentation of the results were simplified to primarily include just 6 of the 17 treatments for 5x5 and 10x5 placements at the 34, 101, and 202 kg N ha^{-1} rates. Nevertheless, in Chapter 2 we also discussed grain yield impacts from 6 banded N placements (5x5, 5x13, 5x20, 10x5, 10x13, and 10x20) at 2 rates (101 and 202 kg N ha^{-1}) to determine how placement was influencing yield and yield components at the two highest N rates.

An additional issue arose with 8-row plots and 17 treatments because topography became challenging as each block encompassed approximately 0.75 ha at ~116m wide on poorly drained soils that were not adequately drained with subsurface tiles. Despite the late 1970's systematic tile drainage installation at 20m widths, the field had several poorly drained depressions. This greatly increased the experiment variability as blocks were not entirely similar in soil type, drainage, and elevation, thus resulting in weaker analyses and higher-than-normal LSD's.

A common handicap for intensive agronomic research is the lack of funding to accomplish high volume sampling and analyses along with the required labor for sampling. One result of this very issue was the lack of zero N plots in 2017. Fortunately, additional funding from the Indiana Corn Marketing Council through the Gary Lamie Graduate Student Assistantship awarded in 2018 allowed for these additional treatments and it permitted R6 biomass and N concentration data to be gathered. Although very interesting results were recorded in 2018 for N uptake and NRE, our conclusions were weakened as only a single site year of data was recorded. Lack of funding, time, and labor also limited the number of site-years of this trial. Purdue's research farms are spread across a wide variety of soils and climates with diverse parent material, native vegetation, and age. Although trials similar to those outlined here (but without the plant N uptake measurements) were replicated by Deere-sponsored trials in Illinois and Iowa, additional resources could have placed more studies in Indiana on different textured soils (e.g. perhaps those more susceptible to ammonia seedling toxicity than the high organic silt loam soil utilized in this trial).

Chapter 3 included large 0.68 ha plots containing 8 treatments with individual blocks covering 5.44 ha. While these extensive blocks limited analyses power in Chapter 2, Chapter 3 was less affected as each field was extremely uniform in soil characteristics. However, an error with the high at-plant N rate resulted in an unbalanced total N rate between split N treatments and 100% at-plant control (AP_224) which received 22 kg ha^{-1} more N. This reduced the likelihood for split N applications to perform better than the at-plant timed applications as less N stress would inevitably occur with the higher N rate. Also, the Pinney Purdue research farm managing the location of this trial lacked capabilities for late-season N applications with coulter injection or Y-Drop™. This led us to work with cooperators to complete the necessary applications. While the cooperators remained the same each year, the V5 application in 2018 was not accomplished with the use of Y-Drop™ streaming as intended but the 24-row applicator was fitted with a drop tube and streaming nozzle. Around the V5 stage in our plots, we were competing with numerous post herbicide applications for equipment access. Our commercial cooperator's machine was dedicated to herbicide applications in many customer fields and were understandably unwilling to swap their machine to Y-Drop™ (as the delay would inherently cost them much more money than they would make applying N for us).

However, the greatest challenge with completing the sidedress trial was not design or treatment execution, but failure to utilize the same streaming approach for each application. This led us to having 3/4 applications utilizing Y-Drop™ (all of 2017 and V12_str in 2018). An additional complication was the location and size of the field site. The entire field extended over 36ha (including end rows and border) and had a perimeter length near 2.5km. Long hours, in addition to a 1.5-2 hour drive to reach the field, limited the amount of in-season measurements recorded. With nearly a half-day of travel to and from the site, sampling had to be simple and efficient to not take away from other experiments that involved higher intensity and more complicated sampling. Whole-plant sampling at R6 took a large, efficient crew most of a day to recover and process plants and ears. Intensive and costly plant sampling to obtain N uptake and NRE data was only performed on 10 plants/plot. With 0.68 ha plots at a plant density of ~70,000 plants ha^{-1}, we were only sampling ~0.021% of the available population. From sampling such a small area it is difficult to know if we were recording a truly representative plant stand, although our best efforts were taken to ensure representative sampling.

4.4 Future Research Suggestions

If agricultural use of synthetic and manure fertilizers continues to contribute to hypoxia zones around the U.S. further restrictive N regulations are inevitable. Universities and commercial companies must find ways of preventing the loss of nutrients to the environment. High-quality agronomic research has continued to improve our understanding of N management decisions and their influence on nutrient uptake, even when a yield benefit may not sufficiently subsidize the additional management practice cost.

Results from Chapter 2 prove that the novel concept of planter-banded N at moderate to high rates placed at the traditional starter fertilizer placement (5cm by 5cm from the seed) can maintain or increase yield in continuous corn compared to lower starter N rates. Further investigation of this concept needs to be researched across the Midwest to validate the concept's feasibility on more soil types and climates, especially in sandy soils where rainfall is limited and irrigation cannot be applied. In sandy soils with limited water, the potential for ammonia toxicity will increase. Even if planter banded N at 40 to 100% of a season N rate is not feasible across all geographies, we witnessed exceptionally high NRE values in 2018 with the 101 kg N ha^{-1} planter banded rate followed by V5 to V6 sidedress of 101 kg N ha^{-1} (suggesting promise for the practice).

This investigation should continue in various crop rotations at the agronomic or economic optimum N rate recommended for the geography.

Alternatively, the likely driving factor behind planter-applied N success and failure is soil moisture and temperature at planting. Soil moisture allows for the “hot zone” surrounding the N band to dilute and therefore become less toxic to corn seedlings as the seminal roots enter the band. Temperature is one factor contributing to germination and emergence rates which could then influence how the young seedlings react to the N band. Soil temperature at the time of planting is influenced by climate and management practices. As planting continues to be pushed earlier, delays are likely to lengthen between planting and emergence.

Planter banded N trials should include additional plant response measurements than what we included in our trial. With delivering high volumes of liquid fertilizer comes additional weight from the storage of fertilizer that could cause compaction in yield loss, especially for rows near tire traffic. I recommend penetrometer readings along with plant measurements (i.e. height, stalk diameter, biomass, and N accumulation) from these rows to determine if compaction is an issue. Harvest should also be performed independently on rows that are determined “compaction prone” to determine if yield reductions occur.

Our research suggests an advantage for 50:50 split N applications between planting and early sidedress, suggesting early growth and development were associated with this management strategy leading to yield improvement. However, to fully understand how 50:50 split N applications between planting and early sidedress are influencing N uptake and growth, I suggest biomass sampling pre-R1 (V6 to V8), at R1, and R6 for biomass and N concentration determination in both stover and grain. Further plant partitioning would provide even further perspectives on N uptake allocations resulting from different N placements during the season.

Currently, only one published University extension paper outlines results from the Y-Drop™ system in agronomic research. The Y-Drop™ systems are rapidly increasing in popularity for farmers and custom applicators. Generally, subsurface applications have been the standard; however, surface applications offer a simpler, higher-speed, and more customizable approach to in-season banding of liquid N. Systems with a similar approach of surface application of N will likely continue to flourish in modern agriculture and should be researched in alternative environments where in-season N loss is greatest and/or soil types inhibit or promote the infiltration of surface applied fertilizers. Environments where early in-season precipitation is excessive will tend to favor in-season applications; however, when paired with a "difficult environment" such as one with high residue cover, drought following N application, and (or) a soil with restricted infiltration, a surface approach would likely be insufficient in delivering N. Alternatively, further research may find that surface applications prove superior to subsurface applications even in "difficult environments" as our knowledge of surface applications in a variety of conditions is weak.

When applications of N are made on the soil surface it has been well documented that timely and sufficient rainfall shortly following application is needed to incorporate the N reducing environmental losses to volatilization. Similarly, surface-applied N treatments under multiple moisture regimes is another interesting area of research as it is well published in the literature that high rainfall favors sidedress applications. More specifically, comparing surface-applied nutrients with multiple placement methods would be interesting. To fully understand surface placement differences (i.e. Y-Drop™), it should be compared versus other surface placements (i.e. single mid-row, broadcast, multi-band; 3, 5, etc.,) at various timings relative to plant development and in multiple environmental conditions.

In Chapter 3, our research was confounded to a surface versus subsurface application even though within-row placements differed. With this in mind, a subsequent 2019 trial was conducted (once again with Deere financial support) at Purdue University under Dr. Tony Vyn that is unrelated to previous work discussed in Chapter 3. In this new trial, a comparison of multiple surface placements (i.e. Y-Drop™ versus mid-row surface banded) will further inform if/when Y-Drop™ is a superior surface placement method. Further research will continue to tell the story of surface-applied N but, hopefully, this story will include more analyses of alternative Y-Drop™ systems.

As previously mentioned, Chapter 3 was a resource-demanding trial which limited the measurements we could take. In an ideal situation, I would have liked to have taken infiltration and penetrometer readings, especially if the trial could have been conducted on multiple sites. Additional biomass sampling at R1 is necessary to determine post-silking N uptake that is likely improved with in-season applications. Additional tool development and advancement are needed to better assess plant nutrient status before N stress occurs and lowers yield potential. For example, measurements either in-field (SPAD, leaf area index, etc.) or via remote sensing (NDVI, NDRE, CCCI, etc.) need to be taken to determine when plants are displaying N stress and eventually better define critical levels (or sufficiency indexes) to determine the economic optimum N rate (EONR) and optimum placements for supplying more N via in-season applications.

Remote sensing technologies are continuing to expand and provide higher correlations to plant traits and more plant-metric predictions. Where applicable, flights should be utilized to acquire data for correlation models or even just imagery for later reference or analyses. Although reliable predictions may not result, imagery provides a great reference for issues that arise when cleaning yield data or when determining if a plot is representative well after the field has been harvested. In my experience cleaning yield data, imagery provides a great reference to more specifically trim ponded areas, planter skips, or other troubled areas that may not show up on a yield monitor. The automated approaches will further enhance data accusation as they provide opportunity for data collection when resources are constrained and have implications for overall cost reductions.

Ideally, each of the trials presented in this thesis would feature multiple hybrids as it is well known that hybrids vary in response to management practices. Although including many hybrids in the previous trials is difficult, increasing the number of hybrids exposed to emerging technologies will better inform crop consultants and farmers about the capabilities of upcoming technologies. Lastly, when researching management practices, I believe using field-scale plots with commercial-sized equipment is best for capturing information relevant to industry. The use of field-scale trials goes a long way in validating the credibility of those creating innovative solutions targeted toward farmers and crop consultants who are changing production practices on U.S. farms.

4.5 Reference

Camberato, J. and B. Nielsen. 2019. Nitrogen management guidelines for corn in Indiana. applied crop research update. http://www.kingcorn.org/news/timeless/NitrogenMgmt.pdf

APPENDIX A. CHAPTER 2 – APPENDIX TABLES AND FIGURES

Table A.1. Mean soil fertility to 20cm depth in each replication (1 to 4) at the Agronomy Center for Research and Education (ACRE) farm site in 2017 for pH, organic matter (OM), cation exchange capacity (CEC), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca).

	pH	OM	CEC	P	K	Mg	Ca
Replication		(%)	(cmol$_c$ kg^{-1})	(mg kg^{-1})		(mg Mg^{-1})	
1	5.9	3.7	21.8	19	128	597	2,333
2	6.4	3.0	18.2	10	119	593	2,094
3	6.0	3.5	21.6	17	136	644	2,436
4	5.9	2.8	17.2	18	138	513	1,794
Mean	**6.1**	**3.3**	**19.7**	**16.0**	**130.3**	**587**	**2,164**

Table A.2. Mean soil fertility to 20cm depth in each replication (1 to 4) at the Agronomy Center for Research and Education (ACRE) farm site in 2018 for pH, organic matter (OM), cation exchange capacity (CEC), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca).

	pH	OM	CEC	P	K	Mg	Ca
Replication		(%)	(cmol$_c$ kg^{-1})	(mg kg^{-1})		(mg Mg^{-1})	
1	6.1	3.7	23.2	23	228	676	2,661
2	6.5	3.3	18.5	15	179	620	2,327
3	6.3	3.7	22.6	27	207	676	2,549
4	6.0	3.4	19.6	25	203	559	2,158
Mean	**6.2**	**3.5**	**21.0**	**22.5**	**204**	**633**	**2,424**

Table A.3. Vegetative (V6 stage) soil nitrate (NO_3^-) and ammonia (NH_4^+) concentrations at two depths taken 20cm from the row (post-sidedress) in 2017 as affected by planter banded N rate followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

Planter N				V6 NO_3^-		V6 NH_4^+	
Placement†	AP	SD	Total	0-30cm	30-60cm	0-30cm	30-60cm
DepthxDist.	(kg N ha^{-1})			(ppm)			
5x5	0	202	202	3.8	4.5	5.3 **b**	3.3
5x5	34	168	202	8.5	4.8	6.5 **ab**	3.5
5x5	101	101	202	12.0	7.8	8.0 **ab**	4.0
5x5	202	0	202	19.8	23.3	8.3 **a**	5.8

†Planter banded N placement 5x5 (cm depth from soil surface x cm distance from seed row)

Table A.4. Vegetative (V3; pre-sidedress and V6; post-sidedress) stage soil nitrate (NO_3^-) and ammonia (NH_4^+) concentrations at two depths taken 20cm from the row in 2018 as affected by planter banded N rate followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

Planter N				V3 NO_3^-		V3 NH_4^+		V6 NO_3^-		V6 NH_4^+	
Placement†	AP	SD	Total	0-30cm	30-60cm	0-30cm	30-60cm	0-30cm	30-60cm	0-30cm	30-60cm
DepthxDist.	(kg N ha^{-1})			(ppm)							
5x5	0	202	202	7.8	4.8	7.9	3.8	5.4 **b**	6.0	3.6 **b**	4.6
5x5	34	168	202	13.9	5.6	15.3	5.6	5.8 **b**	6.2	4.2 **ab**	4.0
5x5	101	101	202	8.7	4.1	8.0	3.6	13.7 **ab**	6.6	6.5 **a**	5.0
5x5	202	0	202	9.4	5.2	9.4	4.8	24.5 **a**	7.1	6.6 **a**	4.6

†Planter banded N placement 5x5 (cm depth from soil surface x cm distance from seed row)

Table A.5. Post V5 final plant population for 2017 and 2018 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement†	AP	SD	Total	Final Plant Populations (plants ha^{-1}) 2017	2018
	(kg N ha^{-1})				
Zero	0	0	0	--	75,800
0x5	101	101	202	82,000	74,900
0x13	101	101	202	83,800	75,700
5x5	0	202	202	81,700	77,100
5x5	34	168	202	81,300	75,400
5x5	101	101	202	83,800	75,800
5x5	202	0	202	83,800	77,200
5x13	101	101	202	83,000	76,300
5x13	202	0	202	82,200	76,300
5x20	101	101	202	83,600	78,100
5x20	202	0	202	84,200	76,600
10x5	34	168	202	82,400	77,800
10x5	101	101	202	80,700	76,900
10x5	202	0	202	80,300	77,400
10x13	101	101	202	81,300	76,800
10x13	202	0	202	82,400	76,600
10x20	101	101	202	83,000	76,400
10x20	202	0	202	82,800	77,500
Mean				**82,500**	**76,600**

†Placement: Treatment comparison between an unfertilized control (Zero) and planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha^{-1})

Table A.6. Method 2. Post V5 final plant population for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Final Plant Populations (plants ha^{-1}) 2017	2018
5x5	83,800	76,400
5x20	82,600	76,300
5x13	83,900	77,400
10x5	80,500	77,100
10x13	81,900	76,700
10x20	82,900	77,000
101_101	82,600	76,700
202_202	82,600	77,000
Mean	**82,600**	**76,800**

†ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table A.7. Cumulative growing degree days (GDD_c; base 10°C) from planting to reach 50% and 90% emergence for 2017 and 2018 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement†	AP	SD	Total	50% Emergence 2017	50% Emergence 2018	90% Emergence 2017	90% Emergence 2018
	(kg N ha^{-1})			(GDD_c)			
Zero	0	0	0	--	52 **ab**	--	73
0x5	101	101	202	70	55 **a**	91	74
0x13	101	101	202	70	52 **ab**	91	71
5x5	0	202	202	70	52 **ab**	91	66
5x5	34	168	202	70	52 **ab**	91	71
5x5	101	101	202	70	52 **ab**	91	66
5x5	202	0	202	70	52 **ab**	91	66
5x13	101	101	202	70	50 **b**	91	69
5x13	202	0	202	70	52 **ab**	91	71
5x20	101	101	202	70	52 **ab**	91	69
5x20	202	0	202	70	52 **ab**	91	66
10x5	34	168	202	70	52 **ab**	91	74
10x5	101	101	202	70	52 **ab**	91	66
10x5	202	0	202	70	52 **ab**	91	66
10x13	101	101	202	70	52 **ab**	91	66
10x13	202	0	202	70	52 **ab**	91	69
10x20	101	101	202	70	52 **ab**	91	69
10x20	202	0	202	70	52 **ab**	91	69

†Placement: Treatment comparison between an unfertilized control (Zero) and planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha^{-1})

Table A.8. Method 1. Cumulative growing degree days (GDD_c; base 10°C) from planting to reach 50% and 90% emergence for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	50% Emergence		90% Emergence	
	(GDD_c)			
	2017	2018	2017	2018
5x5	70	52	91	67
10x5	70	52	91	69
34	70	52	91	71
101	70	52	91	66
202	70	52	91	66

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

Table A.9. Method 2. Cumulative growing degree days (GDD_c; base 10°C) from planting to reach 50% and 90% emergence for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	50% Emergence		90% Emergence	
	(GDD_c)			
	2017	2018	2017	2018
5x5	70	52	91	66
5x13	70	50	91	70
5x20	70	52	91	67
10x5	70	52	91	66
10x13	70	52	91	67
10x20	70	52	91	69
101	70	52	91	66
202	70	52	91	67

†ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table A.10. Leaf area index and SPAD readings for 2017 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

				Leaf Area Index		SPAD		
Planter N	AP	SD	Total	(V15)	(R2-R3)	(V8)	(V12)	(R2-R3)
Placement†	——(kg N ha^{-1})——			7/18	8/11	6/26	7/7	8/11
0x5	101	101	202	3.7	4.2	47.5	52.7	53.5
0x13	101	101	202	3.8	4.5	50.2	54.6	55.6
5x5	0	202	202	3.5	4.4	47.3	55.6	56.7
5x5	34	168	202	3.7	4.0	47.3	51.0	55.3
5x5	101	101	202	3.8	4.5	49.0	53.1	55.7
5x5	202	0	202	3.6	4.2	49.0	52.7	53.8
5x13	101	101	202	3.6	4.5	51.1	54.7	55.4
5x13	202	0	202	4.1	4.8	50.6	54.2	54.1
5x20	101	101	202	3.7	4.4	50.5	54.8	56.4
5x20	202	0	202	3.8	4.6	50.3	53.9	53.2
10x5	34	168	202	3.5	4.2	46.9	53.8	54.0
10x5	101	101	202	4.0	4.5	47.1	53.1	53.0
10x5	202	0	202	3.9	4.8	50.3	54.0	55.3
10x13	101	101	202	3.6	4.3	47.8	54.4	55.0
10x13	202	0	202	4.6	4.8	51.2	55.1	55.3
10x20	101	101	202	3.8	4.2	49.8	54.6	54.3
10x20	202	0	202	3.7	4.8	48.8	55.0	56.4

†Placement: Treatment comparison between planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha^{-1})

Table A.11. Leaf area index and SPAD readings for 2018 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

Planter N	AP	SD	Total	Leaf Area Index			SPAD		
				(V10)	(V15)	(R4)	(V8)	(V10)	(R2-R3)
Placement†	——(kg N ha^{-1})——			6/29	7/10	8/8	6/18	6/28	7/24
Zero	0	0	0	1.9 **d**	2.3 **b**	1.9 **c**	35.9 **b**	32.0 **c**	29.1 **c**
0x5	101	101	202	3.2 **abc**	4.1 **a**	4.6 **ab**	43.8 **a**	44.3 **ab**	49.9 **ab**
0x13	101	101	202	3.5 **abc**	3.9 **a**	4.4 **ab**	45.7 **a**	44.7 **ab**	50.5 **ab**
5x5	0	202	202	2.9 **abc**	3.8 **a**	4.8 **ab**	45.0 **a**	46.2 **ab**	53.3 **ab**
5x5	34	168	202	3.1 **abc**	4.1 **a**	4.4 **ab**	45.1 **a**	46.0 **ab**	51.8 **ab**
5x5	101	101	202	3.8 **ab**	4.6 **a**	4.7 **ab**	46.0 **a**	47.2 **ab**	56.0 **a**
5x5	202	0	202	3.4 **abc**	4.0 **a**	4.2 **ab**	44.9 **a**	44.2 **ab**	52.3 **ab**
5x13	101	101	202	3.2 **abc**	4.0 **a**	4.2 **ab**	46.1 **a**	45.7 **ab**	52.5 **ab**
5x13	202	0	202	4.0 **a**	4.8 **a**	4.9 **a**	48.5 **a**	44.2 **ab**	54.0 **ab**
5x20	101	101	202	3.6 **abc**	4.5 **a**	4.5 **ab**	46.8 **a**	43.8 **ab**	51.8 **ab**
5x20	202	0	202	3.6 **abc**	4.5 **a**	4.6 **ab**	45.7 **a**	45.7 **ab**	54.3 **ab**
10x5	34	168	202	2.7 **cd**	4.0 **a**	4.4 **ab**	44.5 **a**	42.3 **b**	46.1 **b**
10x5	101	101	202	3.6 **abc**	4.3 **a**	3.8 **b**	47.5 **a**	45.8 **ab**	55.4 **a**
10x5	202	0	202	3.6 **abc**	4.5 **a**	4.6 **ab**	47.5 **a**	45.2 **ab**	52.0 **ab**
10x13	101	101	202	3.5 **abc**	4.3 **a**	4.6 **ab**	46.5 **a**	47.7 **a**	50.1 **ab**
10x13	202	0	202	3.7 **abc**	4.5 **a**	5.1 **a**	46.4 **a**	47.4 **ab**	53.9 **ab**
10x20	101	101	202	3.7 **abc**	4.4 **a**	4.7 **ab**	47.5 **a**	46.1 **ab**	53.5 **ab**
10x20	202	0	202	3.2 **abc**	3.9 **a**	4.2 **ab**	44.0 **a**	44.5 **ab**	53.6 **ab**

†Placement: Treatment comparison between an unfertilized control (Zero) and planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha^{-1})

Table A.12. Method 1. Leaf area index for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Leaf Area Index				
	(V15)	(R2)	(V10)	(V15)	(R4)
	7/18/17	8/11/17	6/29/18	7/10/18	8/8/18
5x5	3.7	4.2	3.5	4.3	4.5
10x5	3.8	4.5	3.3	4.2	4.2
34	3.6	4.1	2.9 **b**	4.2 **b**	4.4
101	3.9	4.5	3.7 **a**	4.5 **a**	4.2
202	3.7	4.5	3.6 **a**	4.3 **ab**	4.4

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

Table A.13. Method 2. Leaf area index for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Leaf Area Index				
	(V15)	(R2)	(V10)	(V15)	(R4)
	7/18/17	8/11/17	6/29/18	7/10/18	8/8/18
5x5	3.7	4.3	3.7	4.4	4.5 **ab**
5x13	3.8	4.7	3.6	4.4	4.6 **ab**
5x20	3.8	4.5	3.6	4.5	4.6 **ab**
10x5	4.0	4.6	3.6	4.4	4.2 **b**
10x13	4.0	4.5	3.6	4.4	4.9 **a**
10x20	3.8	4.5	3.5	4.2	4.5 **ab**
101	3.7	4.4 **b**	3.6	4.4	4.4
202	3.9	4.6 **a**	3.6	4.4	4.6

†ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table A.14. Method 1. SPAD for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	SPAD					
	(V8)	(V12)	(R2)	(V8)	(V10)	(R2-R3)
	6/26/17	7/7/17	8/11/17	6/18/18	6/28/18	7/24/18
5x5	48.4	52.3	54.9	45.4	45.9	53.5
10x5	47.9	53.6	54.0	46.5	44.4	51.2
34	47.1	52.4	54.7	44.8	44.1	49.0 **b**
101	48.1	53.1	54.4	46.7	46.5	55.7 **a**
202	49.5	53.3	54.4	46.4	44.8	52.1 **ab**

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

Table A.15. Method 2. SPAD for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	SPAD					
	(V8)	(V12)	(R2)	(V8)	(V10)	(R2-R3)
	6/26/17	7/7/17	8/11/17	6/18/18	6/28/18	7/24/18
5x5	49.0	52.9	54.8	45.5	45.9	54.4
5x13	50.8	54.4	54.8	47.3	44.9	53.3
5x20	50.4	54.3	54.8	46.2	44.7	53.1
10x5	48.4	53.5	53.9	47.5	45.5	53.7
10x13	49.2	54.7	55.1	46.4	47.6	52.0
10x20	49.3	54.8	55.4	45.8	45.3	53.6
101	49.2	54.1	55.0	46.7	46.1	53.2
202	49.9	54.1	54.6	46.2	45.2	53.4

†ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table A.16. Plant height and stalk diameter measurements for 2017 and 2018 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha-1. Different letters indicate a significant difference at p-value <0.05.

				Vegetative Plant Heights†						Final Height†		Stalk Diameters‡	
				(V8)	(V12)	(V15)	(V5)	(V7-V8)	(V10)	(R2)	(R2-R3)	(R5)	(R2-R3)
Planter N	AP	SD	Total	(cm)								(mm)	
Placement§	(kg N ha-1)			6/28/17	7/7/17	7/18/17	6/7/18	6/15/18	6/28/18	8/11/17	7/24/18	9/12/17	7/24/18
Zero	0	0	0	--	--	--	32.4	60.0 **a**	95.4 **a**	--	180.8 **c**	--	17.2 **b**
0x5	101	101	202	73.2	118.6	183.3	35.2	48.4 **bc**	61.3 **bcd**	244.4	257.0 **ab**	24.0	19.8 **a**
0x13	101	101	202	75.5	127.3	194.2	33.0	48.9 **bc**	75.6 **abcd**	239.2	247.5 **ab**	23.7	21.1 **a**
5x5	0	202	202	84.5	127.6	189.8	32.0	48.3 **bc**	60.9 **cd**	229.0	256.7 **ab**	21.5	20.3 **a**
5x5	34	168	202	70.1	115.3	179.9	32.4	55.7 **abc**	71.3 **abcd**	237.6	243.4 **ab**	24.3	19.9 **a**
5x5	101	101	202	77.3	125.0	187.7	32.3	49.9 **bc**	60.4 **cd**	235.6	265.9 **ab**	22.4	21.6 **a**
5x5	202	0	202	78.4	127.9	190.3	35.9	55.7 **abc**	84.6 **abcd**	231.9	243.6 **ab**	24.0	20.5 **a**
5x13	101	101	202	85.8	138.8	203.4	33.3	49.8 **bc**	78.0 **abcd**	238.0	227.9 **b**	23.7	20.6 **a**
5x13	202	0	202	78.9	133.4	196.4	33.3	54.5 **abc**	74.2 **abcd**	240.3	254.1 **ab**	22.8	21.6 **a**
5x20	101	101	202	80.5	134.7	201.6	29.8	51.5 **abc**	83.0 **abcd**	241.2	260.3 **ab**	22.2	21.0 **a**
5x20	202	0	202	76.8	128.2	194.3	33.9	53.7 **abc**	91.0 **abc**	239.7	264.5 **ab**	23.2	22.0 **a**
10x5	34	168	202	76.0	125.6	187.9	33.5	57.2 **ab**	84.7 **abcd**	232.5	238.2 **c**	24.0	20.6 **a**
10x5	101	101	202	73.0	119.4	185.6	33.4	46.8 **c**	64.9 **abcd**	240.5	257.2 **ab**	22.1	21.1 **a**
10x5	202	0	202	84.8	142.0	207.3	33.1	54.5 **abc**	81.1 **abcd**	254.9	258.0 **ab**	24.4	20.7 **a**
10x13	101	101	202	72.9	124.5	188.8	33.6	54.7 **abc**	84.6 **abcd**	236.3	261.2 **ab**	22.9	20.8 **a**
10x13	202	0	202	84.1	139.0	202.7	31.8	46.9 **c**	58.8 **d**	241.3	271.1 **a**	22.8	21.7 **a**
10x20	101	101	202	79.4	132.1	198.9	31.9	54.6 **abc**	85.2 **abcd**	241.5	253.4 **ab**	23.2	21.1 **a**
10x20	202	0	202	77.3	130.5	190.1	33.7	61.4 **a**	92.9 **ab**	228.9	245.1 **ab**	22.8	19.9 **a**

†Plant heights were measured to the tallest natural resting plant component (i.e. leaf or tassel) in 2017 and the tallest fully developed collar in 2018

‡Stalk diameters were measured between the soil surface and first node on the major (thickest) diameter in 2017 and the minor (thinnest) diameter in 2018

§Placement: Treatment comparison between an unfertilized control (Zero) and planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha-1)

Table A.17. Method 1. Plant height and stalk diameter measurements for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

	Vegetative Plant Heights†						Final Heights†		Stalk Diameters‡	
Planter N	(V8)	(V12)	(V15)	(V5)	(V7-V8)	(V10)	(R2)	(R2-R3)	(R5)	(R2-R3)
Placement or	(cm)								(mm)	
N Rate ID§	6/28/17	7/7/17	7/18/17	6/7/18	6/15/18	6/28/18	8/11/17	7/24/18	9/12/17	7/24/18
5x5	75.2	122.7	186.0	33.3	53.6	70.9	235.1	251.6	23.6	20.7
10x5	77.3	127.8	192.4	33.3	52.8	76.9	241.1	251.1	23.4	20.8
34	73.0	120.4	183.9	33.0	56.4 **a**	78.0 **ab**	235.1	240.8 **b**	24.2	20.2
101	75.1	122.2	186.7	32.8	48.3 **b**	62.6 **b**	238.1	261.5 **a**	22.2	21.3
202	81.1	133.9	197.6	34.3	55.0 **a**	82.6 **a**	241.1	251.8 **ab**	24.2	20.6

†Plant heights were measured to the tallest natural resting plant component (i.e. leaf or tassel) in 2017 and the tallest fully developed collar in 2018
‡Stalk diameters were measured between the soil surface and first node on the major (thickest) diameter in 2017 and the minor (thinnest) diameter in 2018
§ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

Table A.18. Method 2. Plant height and stalk diameter measurements for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID§	Vegetative Plant Heights†						Final Height†		Stalk Diameters‡	
	(V8)	(V12)	(V15)	(V5)	(V7-V8)	(V10)	(R2)	(R2-R3)	(R2)	(R2-R3)
	(cm)								(mm)	
	6/28/17	7/7/17	7/18/17	6/7/18	6/15/18	6/28/18	8/11/17	7/24/18	9/12/17	7/24/18
5x5	77.8	126.4	189.0	33.9	52.4 **ab**	70.8	233.8	256.3 **ab**	23.2	21.1
5x13	82.3	136.1	199.9	33.3	52.1 **b**	76.1	239.1	241.0 **b**	23.3	21.1
5x20	78.7	131.4	198.0	31.8	52.6 **ab**	87.0	240.5	262.4 **ab**	22.7	21.5
10x5	78.0	129.1	194.9	33.2	50.6 **b**	73.0	246.2	257.6 **ab**	23.0	20.9
10x13	77.7	130.7	194.8	32.7	50.8 **b**	71.7	238.3	266.1 **a**	22.9	21.2
10x20	78.4	131.3	194.5	32.8	58.0 **a**	89.1	235.2	249.2 **ab**	23.0	20.5
101	78.1	129.1	194.3	32.4	51.2 **b**	76.0	238.8	254.3	22.8	21.0
202	79.6	132.9	196.1	33.5	54.4 **a**	80.2	238.4	256.6	23.3	21.1

†Plant heights were measured to the tallest natural resting plant component (i.e. leaf or tassel) in 2017 and the tallest fully developed collar in 2018

‡Stalk diameters were measured between the soil surface and first node on the major (thickest) diameter in 2017 and the minor (thinnest) diameter in 2018

§ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table A.19. Cumulative growing degree days (GDD_c; base 10°C) from planting to reach 50% silk and tassel development and anthesis silking interval (ASI; days) for 2017 and 2018 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement †	AP	SD	Total	Silking		Tasseling		ASI	
				———(GDDc)———				——(± Days)——	
	—(kg N ha-1)—			2017	2018	2017	2018	2017	2018
Zero	0	0	0	--	865 **a**	--	835 **a**	--	2.5 **a**
0x5	101	101	202	770	803 **b**	774	807 **b**	-0.3	-0.3 **b**
0x13	101	101	202	767	791 **b**	771	798 **b**	-0.3	-0.5 **b**
5x5	0	202	202	782	797 **b**	782	798 **b**	0.0	0.0 **b**
5x5	34	168	202	786	794 **b**	794	801 **b**	-0.7	-0.5 **b**
5x5	101	101	202	782	766 **b**	782	777 **b**	0.0	-1.0 **b**
5x5	202	0	202	782	803 **b**	786	814 **b**	-0.3	-0.8 **b**
5x13	101	101	202	782	794 **b**	782	791 **b**	0.0	0.3 **b**
5x13	202	0	202	782	775 **b**	782	777 **b**	0.0	-0.3 **b**
5x20	101	101	202	786	772 **b**	786	773 **b**	0.0	-0.3 **b**
5x20	202	0	202	782	785 **b**	782	784 **b**	0.0	0.0 **b**
10x5	34	168	202	779	794 **b**	779	794 **b**	0.0	0.0 **b**
10x5	101	101	202	782	782 **b**	794	791 **b**	-1.0	-0.8 **b**
10x5	202	0	202	782	791 **b**	782	798 **b**	0.0	-0.5 **b**
10x13	101	101	202	782	779 **b**	786	773 **b**	-0.3	0.3 **b**
10x13	202	0	202	782	785 **b**	782	787 **b**	0.0	-0.3 **b**
10x20	101	101	202	782	769 **b**	782	767 **b**	0.0	0.0 **b**
10x20	202	0	202	782	772 **b**	786	771 **b**	-0.3	0.0 **b**

†Placement: Treatment comparison between an unfertilized control (Zero) and planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha^{-1})

Table A.20. Method 1. Cumulative growing degree days (GDD_c; base 10°C) from planting to reach 50% silk and tassel development and anthesis silking interval (ASI; days) for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Silking (GDD_c)		Tasseling (GDD_c)		ASI (± Days)	
	2017	2018	2017	2018	2017	2018
5x5	783	785	787	794	-0.3	-0.7
10x5	781	789	786	794	-0.4	-0.3
34	782	794	786	797	-0.3	-0.3
101	782	774	788	785	-0.5	-0.8
202	782	794	785	805	-0.2	-0.6

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

Table A.21. Method 2. Cumulative growing degree days (GDD_c; base 10°C) from planting to reach 50% silk and tassel development and anthesis silking interval (ASI; days) for 2017 and 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Silking (GDD_c)		Tasseling (GDD_c)		ASI (± Days)	
	2017	2018	2017	2018	2017	2018
5x5	782	778	785	791	-0.2	-0.9 **b**
5x13	782	784	782	784	0.0	0.0 **a**
5x20	785	777	785	778	0.0	-0.1 **ab**
10x5	782	788	789	794	-0.6	-0.5 **ab**
10x13	782	779	785	779	-0.2	0.0 **a**
10x20	782	770	785	770	-0.2	0.0 **a**
101	783	773	786	784	-0.2	-0.2
202	782	785	785	790	-0.1	-0.3

†ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table A.22. Flowering (R1) earleaf nutrient concentrations for N in 2017 and 2018 and P, K, Ca, Mg, S, Zn, Mn, Fe, Cu, B, and Al for 2017 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

				2017	2018	2017										
				Flowering (R1) Earleaf Nutrient Concentration												
Planter N	AP	SD	Total	N		P	K	Ca	Mg	S	Zn	Mn	Fe	Cu	B	Al
Placement†	(kg N ha^{-1})			(%)							(mg kg^{-1})					
Zero	0	0	0	--	1.19 **b**	--	--	--	--	--	--	--	--	--	--	--
0x5	101	101	202	2.79	2.29 **a**	0.33	2.23	0.31	0.23	0.17	21.3	55.5	84.3	9.5	7.3	18.5
0x13	101	101	202	2.98	2.25 **a**	0.34	2.18	0.32	0.27	0.19	21.8	46.0	81.3	9.8	7.5	26.0
5x5	0	202	202	3.08	2.58 **a**	0.36	2.16	0.36	0.28	0.19	21.0	41.3	87.0	10.8	8.3	18.3
5x5	34	168	202	2.88	2.46 **a**	0.32	2.23	0.30	0.21	0.18	21.3	53.0	82.0	9.8	7.3	18.3
5x5	101	101	202	2.89	2.73 **a**	0.32	2.15	0.35	0.26	0.18	21.3	41.5	83.8	9.8	6.3	32.5
5x5	202	0	202	2.71	2.32 **a**	0.34	2.18	0.31	0.24	0.17	19.5	51.0	79.3	9.5	7.8	13.3
5x13	101	101	202	2.95	2.41 **a**	0.37	2.28	0.36	0.30	0.19	21.0	42.8	82.8	11.3	8.0	21.8
5x13	202	0	202	2.97	2.61 **a**	0.33	2.14	0.34	0.29	0.19	21.8	50.8	80.3	10.8	7.3	29.5
5x20	101	101	202	2.90	2.08 **a**	0.33	2.09	0.34	0.29	0.18	20.5	40.5	82.0	9.5	8.0	19.0
5x20	202	0	202	2.85	2.43 **a**	0.35	2.12	0.34	0.29	0.18	25.8	48.8	83.5	9.3	8.3	25.3
10x5	34	168	202	2.80	2.23 **a**	0.31	2.25	0.35	0.28	0.18	21.0	45.3	82.3	9.8	7.5	12.0
10x5	101	101	202	2.86	2.11 **a**	0.32	2.16	0.34	0.27	0.18	21.8	44.3	83.0	10.0	7.0	30.0
10x5	202	0	202	3.01	2.50 **a**	0.37	2.34	0.31	0.24	0.19	21.0	58.5	80.5	10.3	8.3	11.5
10x13	101	101	202	2.93	2.37 **a**	0.32	2.18	0.33	0.27	0.19	21.3	44.3	80.5	10.5	7.5	16.0
10x13	202	0	202	3.11	2.41 **a**	0.37	2.19	0.37	0.31	0.20	23.3	49.8	88.0	10.8	8.3	30.8
10x20	101	101	202	3.13	2.40 **a**	0.35	2.23	0.36	0.27	0.20	21.8	42.0	89.0	10.5	7.0	24.0
10x20	202	0	202	3.13	2.20 **a**	0.34	2.24	0.36	0.30	0.20	23.3	60.3	86.3	11.3	8.3	17.0

†Placement: Treatment comparison between an unfertilized control (Zero) and planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha^{-1})

Table A.23. Method 1. Flowering (R1) earleaf nutrient concentrations for P, K, Ca, Mg, S, Zn, Mn, Fe, Cu, B, and Al for 2017 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Flowering (R1) Earleaf Nutrient Concentrations										
	P	K	Ca	Mg	S	Zn	Mn	Fe	Cu	B	Al
	(%)					(mg kg^{-})					
5x5	0.33	2.18	0.32	0.24	0.18	20.7	48.5	81.7	9.7	7.1	21.3
10x5	0.33	2.25	0.33	0.26	0.18	21.3	49.3	81.9	10.0	7.6	17.8
34	0.31 **b**	2.24	0.33	0.24	0.18	21.1	49.1	82.1	9.8	7.4 **ab**	15.1 **ab**
101	0.32 **ab**	2.16	0.35	0.26	0.18	21.5	42.9	83.4	9.9	6.6 **b**	31.3 **a**
202	0.36 **a**	2.26	0.31	0.24	0.18	20.3	54.8	79.9	9.9	8.0 **a**	12.4 **b**

†ID: Band placements of 5x5 and 10x5 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 34, 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 34, 101, and 202 kg N ha^{-1} (averaged across band placements 5x5 and 10x5)

Table A.24. Method 2. Flowering (R1) earleaf nutrient concentrations for N in 2017 and 2018 and P, K, Ca, Mg, S, Zn, Mn, Fe, Cu, B, and Al for 2017 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	2017	2018	2017										
	Flowering (R1) Earleaf Nutrient Concentrations												
	N		P	K	Ca	Mg	S	Zn	Mn	Fe	Cu	B	Al
	(%)							(mg kg^{-1})					
5x5	2.80	2.55	7.27	2.16	0.33	0.25	0.17	20.4	46.3	81.5	9.6	7.0	22.9
5x13	2.96	2.51	0.35	2.21	0.35	0.30	0.19	21.4	46.8	81.5	11.0	7.6	25.6
5x20	2.87	2.26	0.34	2.10	0.34	0.29	0.18	23.1	44.6	82.8	9.4	8.1	22.1
10x5	2.93	2.30	0.35	2.25	0.32	0.25	0.18	21.4	51.4	81.8	10.1	7.6	20.8
10x13	3.02	2.39	0.34	2.18	0.35	0.29	0.19	22.3	47.0	84.3	10.6	7.9	23.4
10x20	3.13	2.30	0.34	2.23	0.36	0.29	0.20	22.5	51.1	87.6	10.9	7.6	20.5
101	2.94	2.35	0.33	2.18	0.35	0.28	0.18	21.3	42.5 **b**	83.5	10.3	7.3	23.9
202	2.96	2.41	2.85	2.20	0.34	0.28	0.19	22.4	53.2 **a**	83.0	10.3	8.0	21.2

†ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table A.25. Kernel number $plant^{-1}$, mean individual kernel weight (0% H_2O), harvest moisture, and grain yield (15.5% H_2O) for 2017 and 2018 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

				Kernel Number		Kernel Weight		Harvest Moisture		Grain Yield	
Planter N	AP	SD	Total	(kernels $plant^{-1}$)		(mg $kernel^{-1}$)		(%)		(Mg ha^{-1})	
Placement†	(kg N ha^{-1})			2017	2018	2017	2018	2017	2018	2017	2018
Zero	0	0	0	--	126 **d**	--	170 **c**	--	20.9	--	3.08 **f**
0x5	101	101	202	502	427 **bc**	295	270 **ab**	18.3	23.2	13.23	11.29 **bcde**
0x13	101	101	202	508	434 **abc**	313	259 **b**	18.9	22.4	14.38	11.55 **bcde**
5x5	0	202	202	516	469 **ab**	330	276 **ab**	18.8	24.4	14.73	12.84 **abc**
5x5	34	168	202	496	435 **abc**	315	273 **ab**	18.9	23.6	14.88	12.34 **abcde**
5x5	101	101	202	533	522 **a**	321	281 **ab**	18.7	21.4	13.60	13.67 **a**
5x5	202	0	202	516	443 **abc**	292	262 **ab**	18.6	22.3	14.03	11.69 **abcde**
5x13	101	101	202	542	379 **c**	334	255 **b**	18.6	22.1	14.54	11.03 **cde**
5x13	202	0	202	502	440 **abc**	317	270 **ab**	18.1	21.2	13.94	11.41 **abcde**
5x20	101	101	202	520	448 **abc**	320	279 **ab**	18.4	22.4	14.09	12.26 **abcde**
5x20	202	0	202	514	459 **abc**	300	268 **ab**	18.7	21.8	14.01	12.91 **ab**
10x5	34	168	202	515	427 **bc**	318	267 **ab**	19.1	23.1	13.71	10.63 **de**
10x5	101	101	202	495	478 **ab**	296	292 **a**	18.7	22.1	14.02	12.69 **abcd**
10x5	202	0	202	527	448 **abc**	344	266 **ab**	18.8	21.7	14.11	12.29 **abcde**
10x13	101	101	202	519	447 **abc**	334	272 **ab**	18.5	21.2	13.51	11.61 **abcde**
10x13	202	0	202	519	456 **abc**	305	269 **ab**	17.9	23.3	14.44	11.52 **bcde**
10x20	101	101	202	517	444 **abc**	322	279 **ab**	17.8	21.5	13.63	12.70 **abc**
10x20	202	0	202	516	420 **bc**	319	262 **ab**	18.6	22.5	13.53	10.35 **e**

†Placement: Treatment comparison between an unfertilized control (Zero) and planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha^{-1})

Table A.26. Physiological maturity (R6) biomass and N uptake accumulation for grain, stover, cob, and total for 2018 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha-1. Different letters indicate a significant difference at p-value <0.05.

				Maturity (R6) Biomass Accumulation				Maturity (R6) Nitrogen Accumulation			
Planter N	AP	SD	Total	Grain	Stover	Cob	Total	Grain	Stover	Cob	Total
Placement†	(kg N ha-1)			(kg ha-1)				(kg N ha-1)			
Zero	0	0	0	2,072 **b**	4,818 **c**	571 **c**	7,461 **c**	18.2 **b**	23.8 **c**	4.3 **d**	46.3 **c**
0x5	101	101	202	9,773 **a**	8,134 **ab**	1,211 **ab**	19,117 **ab**	99.0 **a**	58.1 **ab**	9.4 **abc**	166.5 **ab**
0x13	101	101	202	9,619 **a**	8,131 **ab**	1,010 **b**	18,760 **ab**	94.5 **a**	52.1 **ab**	7.3 **c**	153.9 **ab**
5x5	0	202	202	10,484 **a**	7,343 **b**	1,227 **ab**	19,055 **ab**	111.7 **a**	50.4 **ab**	10.0 **abc**	172.2 **ab**
5x5	34	168	202	10,065 **a**	7,488 **ab**	1,244 **ab**	18,796 **ab**	104.0 **a**	49.7 **ab**	10.7 **ab**	164.4 **ab**
5x5	101	101	202	11,733 **a**	9,471 **a**	1,350 **ab**	22,554 **a**	124.4 **a**	72.7 **a**	10.3 **abc**	207.4 **a**
5x5	202	0	202	9,671 **a**	8,040 **ab**	1,190 **ab**	19,001 **ab**	95.3 **a**	52.9 **ab**	8.9 **abc**	157.1 **ab**
5x13	101	101	202	9,097 **a**	7,772 **ab**	1,156 **b**	18,024 **ab**	91.7 **a**	44.8 **bc**	9.5 **abc**	146.0 **b**
5x13	202	0	202	10,698 **a**	8,987 **ab**	1,267 **ab**	20,952 **ab**	111.1 **a**	64.0 **ab**	9.2 **abc**	184.2 **ab**
5x20	101	101	202	11,022 **a**	8,851 **ab**	1,565 **a**	21,438 **ab**	111.8 **a**	56.8 **ab**	12.0 **a**	180.7 **ab**
5x20	202	0	202	11,003 **a**	9,130 **ab**	1,280 **ab**	21,413 **ab**	112.2 **a**	64.3 **ab**	10.1 **abc**	186.6 **ab**
10x5	34	168	202	9,470 **a**	7,505 **ab**	1,088 **b**	18,063 **ab**	103.4 **a**	57.4 **ab**	8.2 **bc**	169.0 **ab**
10x5	101	101	202	11,083 **a**	8,603 **ab**	1,302 **ab**	20,988 **ab**	119.5 **a**	63.4 **ab**	9.3 **abc**	192.2 **ab**
10x5	202	0	202	9,908 **a**	7,995 **ab**	1,145 **b**	19,047 **ab**	101.5 **a**	55.0 **ab**	9.2 **abc**	165.7 **ab**
10x13	101	101	202	10,845 **a**	8,231 **ab**	1,277 **ab**	20,354 **ab**	110.5 **a**	49.9 **ab**	10.1 **abc**	170.4 **ab**
10x13	202	0	202	9,752 **a**	8,076 **ab**	1,174 **b**	19,002 **ab**	99.4 **a**	53.4 **ab**	9.1 **abc**	161.9 **ab**
10x20	101	101	202	10,477 **a**	8,579 **ab**	1,285 **ab**	20,341 **ab**	111.4 **a**	59.2 **ab**	10.5 **ab**	181.1 **ab**
10x20	202	0	202	9,176 **a**	7,562 **ab**	1,179 **ab**	17,918 **b**	92.8 **a**	51.2 **ab**	8.9 **bc**	152.8 **ab**

†Placement: Treatment comparison between an unfertilized control (Zero) and planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha-1)

Table A.27. Method 2. Physiological maturity (R6) biomass and N uptake accumulation for grain, stover, cob, and total for 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID†	Maturity (R6) Biomass Accumulation				Maturity (R6) Nitrogen Accumulation			
	Grain	Stover	Cob	Total	Grain	Stover	Cob	Total
	(kg ha^{-1})				(kg N ha^{-1})			
5x5	10,849	8,901	1,282 **ab**	21,031	111.9	64.2	9.7	185.8
5x13	9,897	8,379	1,211 **b**	19,488	101.4	54.4	9.3	165.1
5x20	11,012	8,991	1,422 **a**	21,425	112.0	60.6	11.0	183.6
10x5	10,496	8,299	1,223 **ab**	20,018	110.5	59.2	9.2	179.0
10x13	10,299	8,154	1,226 **ab**	19,678	104.9	51.6	9.6	166.1
10x20	9,827	8,071	1,232 **ab**	19,130	102.1	55.2	9.7	167.0
101	10,709	8,585	1,322 **a**	20,616 **a**	111.6 **a**	57.8	10.3 **a**	179.6
202	10,051	8,323	1,207 **b**	19,580 **b**	102.3 **b**	57.0	9.2 **b**	168.5

†ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table A.28. Physiological maturity (R6) biomass and N uptake accumulation for grain, stover, cob, and total for 2018 as affected by at-plant (AP) planter banded N placement at multiple rates followed by V5-V6 sidedress (SD) to balance all treatments at a common total N rate of 202 kg N ha^{-1}. Different letters indicate a significant difference at p-value <0.05.

				Maturity (R6) N Concentrations			Maturity (R6) N Fertilizer Efficiencies				
Planter N	AP	SD	Total	Grain	Stover	Cob	NHI	HI	NRE	NUE	NIE
Placement†	(kg N ha^{-1})			(%)						(kg kg^{-1})	
Zero	0	0	0	0.89 **b**	0.50 **b**	0.78	--	29.5 **b**	--		
0x5	101	101	202	1.01 **ab**	0.71 **a**	0.78	63.5	54.5 **a**	67.8 **ab**	42.8	64.8
0x13	101	101	202	0.98 **ab**	0.63 **ab**	0.74	64.5	54.0 **a**	60.8 **ab**	41.9	70.6
5x5	0	202	202	1.06 **a**	0.70 **ab**	0.82	68.5	58.8 **a**	70.8 **ab**	46.7	65.7
5x5	34	168	202	1.03 **ab**	0.67 **ab**	0.86	67.5	57.5 **a**	66.5 **ab**	44.4	67.4
5x5	101	101	202	1.06 **a**	0.77 **a**	0.77	63.5	55.5 **a**	90.3 **a**	53.7	60.2
5x5	202	0	202	0.99 **ab**	0.65 **ab**	0.75	64.3	54.3 **a**	61.7 **ab**	41.0	66.7
5x13	101	101	202	1.01 **ab**	0.58 **ab**	0.82	67.3	53.9 **a**	56.2 **b**	39.0	69.8
5x13	202	0	202	1.04 **a**	0.71 **a**	0.72	63.5	54.4 **a**	77.4 **ab**	47.9	61.9
5x20	101	101	202	1.02 **ab**	0.64 **ab**	0.77	66.3	55.3 **a**	75.5 **ab**	49.7	65.7
5x20	202	0	202	1.03 **ab**	0.70 **ab**	0.79	63.8	54.8 **a**	78.8 **ab**	49.6	63.2
10x5	34	168	202	1.10 **a**	0.77 **a**	0.75	64.0	55.8 **a**	68.8 **ab**	41.1	59.3
10x5	101	101	202	1.08 **a**	0.73 **a**	0.72	65.8	56.3 **a**	82.0 **ab**	50.1	62.5
10x5	202	0	202	1.02 **ab**	0.69 **ab**	0.80	64.8	55.3 **a**	67.3 **ab**	43.5	65.6
10x13	101	101	202	1.01 **ab**	0.61 **ab**	0.79	68.8	56.8 **a**	69.8 **ab**	48.7	70.5
10x13	202	0	202	1.02 **ab**	0.66 **ab**	0.78	65.0	54.8 **a**	65.0 **ab**	42.7	65.7
10x20	101	101	202	1.06 **a**	0.70 **ab**	0.82	65.5	55.3 **a**	75.8 **ab**	46.7	62.0
10x20	202	0	202	1.01 **ab**	0.68 **ab**	0.76	64.5	54.5 **a**	60.3 **ab**	39.5	66.4

†Placement: Treatment comparison between an unfertilized control (Zero) and planter band N placement (0x5, 0x13, 5x5, 5x13, 5x20, 10x5, 10x13, or 10x20) at rates of 0, 34, 101, or 202 kg N ha^{-1})

Table A.29. Method 2. Physiological maturity (R6) plant N concentration in grain, stover, and cob. Nitrogen harvest index (NHI), harvest index (HI), N recovery efficiency (NRE), N use efficiency (NUE), and N internal efficiency (NIE) for 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement or N Rate ID‡	Maturity (R6) N Concentrations			Maturity (R6) N Fertilizer Efficiencies				
	Grain	Stover	Cob†	NHI	HI	NRE	NUE	NIE
	(%)						($kg\ kg^{-1}$)	
5x5	1.03	0.72	0.76	63.9	55.0	78.0.	48.2	63.0
5x13	1.02	0.64	0.77	65.4	54.2	66.8	43.5	65.9
5x20	1.02	0.67	0.78	65.0	55.0	77.1	49.7	64.4
10x5	1.05	0.71	0.76	65.3	55.8	74.6	46.8	64.1
10x13	1.01	0.64	0.79	66.9	55.8	67.4	45.7	68.1
10x20	1.03	0.69	0.79	65.0	54.9	680	43.1	64.2
101	1.04 **a**	0.67	0.78	66.2 **a**	55.5	74.9	48.0 **a**	65.1
202	1.02 **b**	0.68	0.77	64.3 **b**	54.7	68.7	44.2 **b**	64.8

†Not statistically analyzed, only one replication of data.

‡ID: Band placements of 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20 (cm depth from soil surface x cm distance from seed row; averaged across banded N rates of 101, and 202 kg N ha^{-1}) and at-plant banded N rates of 101 and 202 kg N ha^{-1} (averaged across band placements 5x5, 5x13, 5x20, 10x5, 10x13, and 10x20)

Table A.30. Method 1. Placement by at-plant (AP) N rate interaction differences on leaf area index for 2018 as affected by planter banded N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement†	Planter N Rate	Leaf Area Index 8/8/18
DepthxDist.	kg N ha^{-1}	(R4)
5x5	34	4.4 **ab**
5x5	101	4.7 **a**
5x5	202	4.2 **ab**
10x5	34	4.4 **ab**
10x5	101	3.8 **b**
10x5	202	4.6 **ab**

†Planter banded N at a depth from the soil surface of 5 or 10cm at a distance from the seed row of 5cm

Table A.31. Method 2. Placement by at-plant (AP) N rate interaction differences on vegetative plant heights in 2017 and 2018 and leaf area index, stalk diameters, and physiological maturity (R6) stover N concentration in 2018 as affected by planter band N and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N	Planter	Vegetative Plant Heights†				Leaf Area Index		Stalk Diameters‡	R6 N Concentration
Placement§	N Rate	(V8)	(V12)	(V7-V8)	(V10)	(V15)	(R4)	(R2-R3)	Stover
DepthxDist.	kg N ha^{-1}	6/28/17	7/7/17	6/15/18	6/28/18	7/10/18	8/8/18	7/24/18	(%)
5x5	101	77.3 **ab**	125.0 **ab**	49.9 **b**	60.4 **b**	4.6 **ab**	4.7 **ab**	21.6 **ab**	0.77 **a**
5x5	202	78.4 **ab**	127.9 **ab**	55.7 **ab**	84.6 **ab**	4.0 **ab**	4.2 **ab**	20.5 **ab**	0.65 **ab**
5x13	101	85.8 **a**	138.8 **ab**	49.8 **b**	78.0 **ab**	4.0 **ab**	4.2 **ab**	20.6 **ab**	0.58 **b**
5x13	202	78.9 **ab**	133.4 **ab**	54.5 **ab**	74.2 **ab**	4.8 **a**	4.9 **a**	21.6 **ab**	0.71 **ab**
5x20	101	80.5 **ab**	134.7 **ab**	51.5 **b**	83.0 **ab**	4.5 **ab**	4.5 **ab**	21.0 **ab**	0.64 **ab**
5x20	202	76.8 **ab**	128.2 **ab**	53.7 **ab**	91.0 **ab**	4.5 **ab**	4.6 **ab**	22.0 **a**	0.70 **ab**
10x5	101	73.0 **b**	119.4 **b**	46.8 **b**	64.9 **ab**	4.3 **ab**	3.8 **b**	21.1 **ab**	0.73 **ab**
10x5	202	84.8 **ab**	142.0 **a**	54.5 **ab**	81.1 **ab**	4.5 **ab**	4.6 **ab**	20.7 **ab**	0.69 **ab**
10x13	101	72.9 **b**	124.5 **ab**	54.7 **ab**	84.6 **ab**	4.3 **ab**	4.6 **ab**	20.8 **ab**	0.61 **ab**
10x13	202	84.1 **ab**	139.0 **ab**	46.9 **b**	58.8 **b**	4.5 **ab**	5.1 **a**	21.7 **ab**	0.66 **ab**
10x20	101	79.4 **ab**	132.1 **ab**	54.6 **ab**	85.2 **ab**	4.4 **ab**	4.7 **ab**	21.1 **ab**	0.70 **ab**
10x20	202	77.3 **ab**	130.5 **ab**	61.4 **a**	92.9 **a**	3.9 **b**	4.2 **ab**	19.9 **b**	0.68 **ab**

†Plant heights were measured to the tallest natural resting plant component (i.e. leaf or tassel) in 2017 and the tallest fully developed collar in 2018

‡Stalk diameters were measured between the soil surface and first node and on the minor (thinnest) diameter

§Planter banded N at a depth from the soil surface of 5 or 10cm at a distance from the seed row of 5, 13, or 20cm

Table A.32. Method 2. Placement by at-plant (AP) N rate interaction differences on physiological maturity (R6) grain and total biomass accumulation, grain, stover, and total R6 N accumulation, N recovery efficiency (NRE), and N use efficiency (NUE) in 2018 as affected by planter band N placement and rate. Different letters indicate a significant difference at p-value <0.05.

Planter N Placement†	Planter N Rate	R6 Biomass Accumulation		R6 N Accumulation			R6 N Fertilizer Efficiencies	
		Grain	Total	Grain	Stover	Total	NRE	NUE
DepthxDist.	kg N ha^{-1}	———(kg ha^{-1}) ———		————(kg N ha^{-1})————			(%)	(kg kg^{-1})
5x5	101	11,733 **a**	22,554 **a**	124.4 **a**	72.7 **a**	207.4 **a**	90.3 **a**	53.7 **a**
5x5	202	9,671 **ab**	19,001 **ab**	95.3 **ab**	52.9 **ab**	157.1 **ab**	61.7 **ab**	41.0 **ab**
5x13	101	9,097 **b**	18,024 **b**	91.7 **b**	44.8 **b**	146.0 **b**	56.2 **b**	39.0 **b**
5x13	202	10,698 **ab**	20,952 **ab**	111.1 **ab**	64.0 **ab**	184.2 **ab**	77.4 **ab**	47.9 **ab**
5x20	101	11,022 **ab**	21,438 **ab**	111.8 **ab**	56.8 **ab**	180.7 **ab**	75.5 **ab**	49.7 **ab**
5x20	202	11,003 **ab**	21,413 **ab**	112.2 **ab**	64.3 **ab**	186.6 **ab**	78.8 **ab**	49.6 **ab**
10x5	101	11,083 **ab**	20,988 **ab**	119.5 **ab**	63.4 **ab**	192.2 **ab**	82.0 **ab**	50.1 **ab**
10x5	202	9,908 **ab**	19,047 **ab**	101.5 **ab**	55.0 **ab**	165.7 **ab**	67.3 **ab**	43.5 **ab**
10x13	101	10,845 **ab**	20,354 **ab**	110.5 **ab**	49.9 **ab**	170.4 **ab**	69.8 **ab**	48.7 **ab**
10x13	202	9,752 **ab**	19,002 **ab**	99.4 **ab**	53.4 **ab**	161.9 **ab**	65.0 **ab**	42.7 **ab**
10x20	101	10,477 **ab**	20,341 **ab**	111.4 **ab**	59.2 **ab**	181.1 **ab**	75.**8ab**	46.7 **ab**
10x20	202	9,176 **b**	17,918 **b**	92.8 **b**	51.2 **ab**	152.8 **b**	60.3 **b**	39.5 **b**

†Planter banded N at a depth from the soil surface of 5 or 10cm at a distance from the seed row of 5, 13, or 20cm

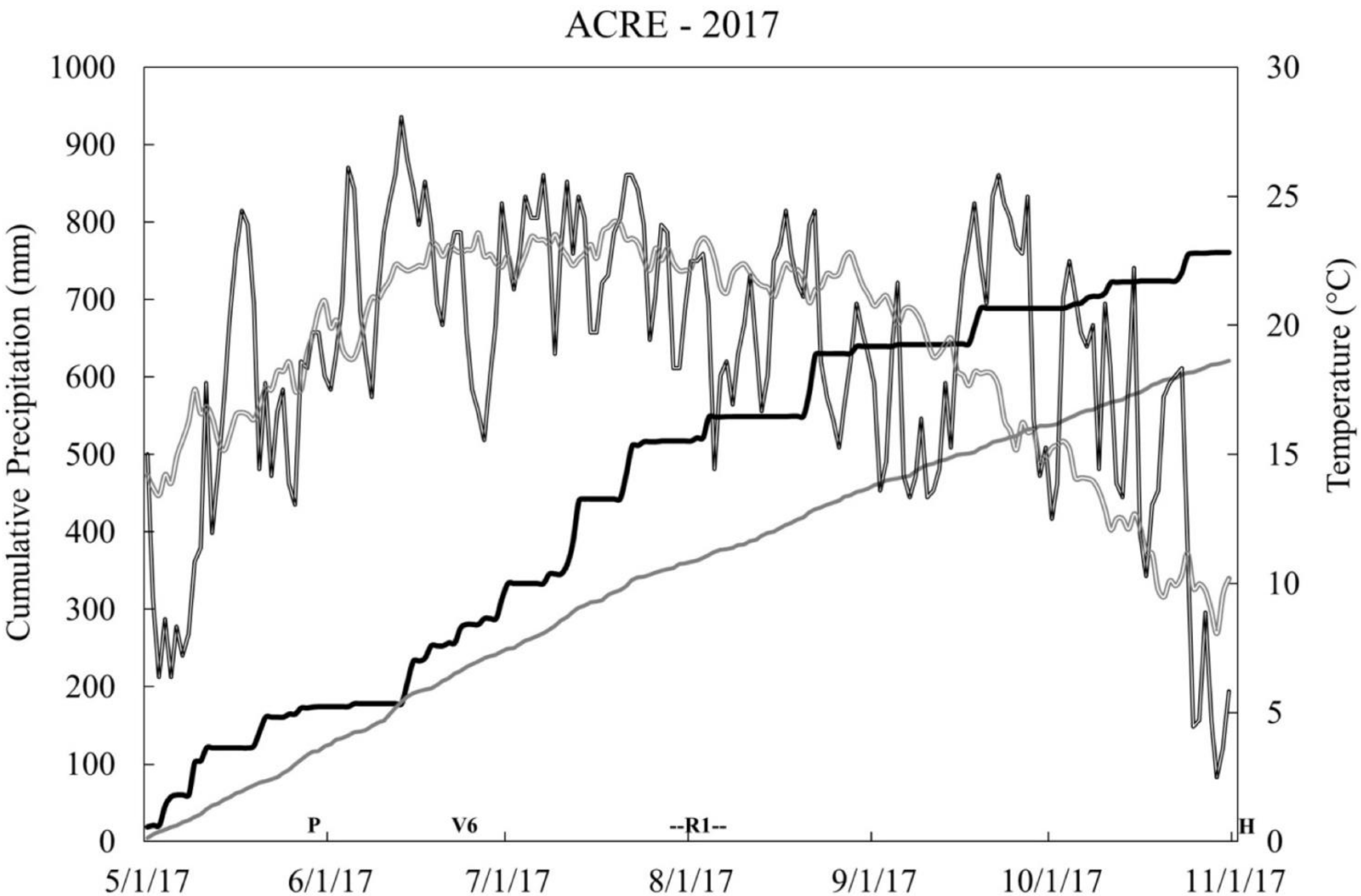

Figure A.1. Daily mean temperatures (°C) and precipitation (mm day-1) during the 2017 growing season and the historic 30-year mean (1988-2017) at the Agronomy Center for Research and Education (ACRE) farm near West Lafayette, Indiana. Field activities are noted as; planting (P: 5/24), V5-V6 N application (V6: 6/22), 50% flowering (R1: ~8/2), and harvest (H: 11/8).

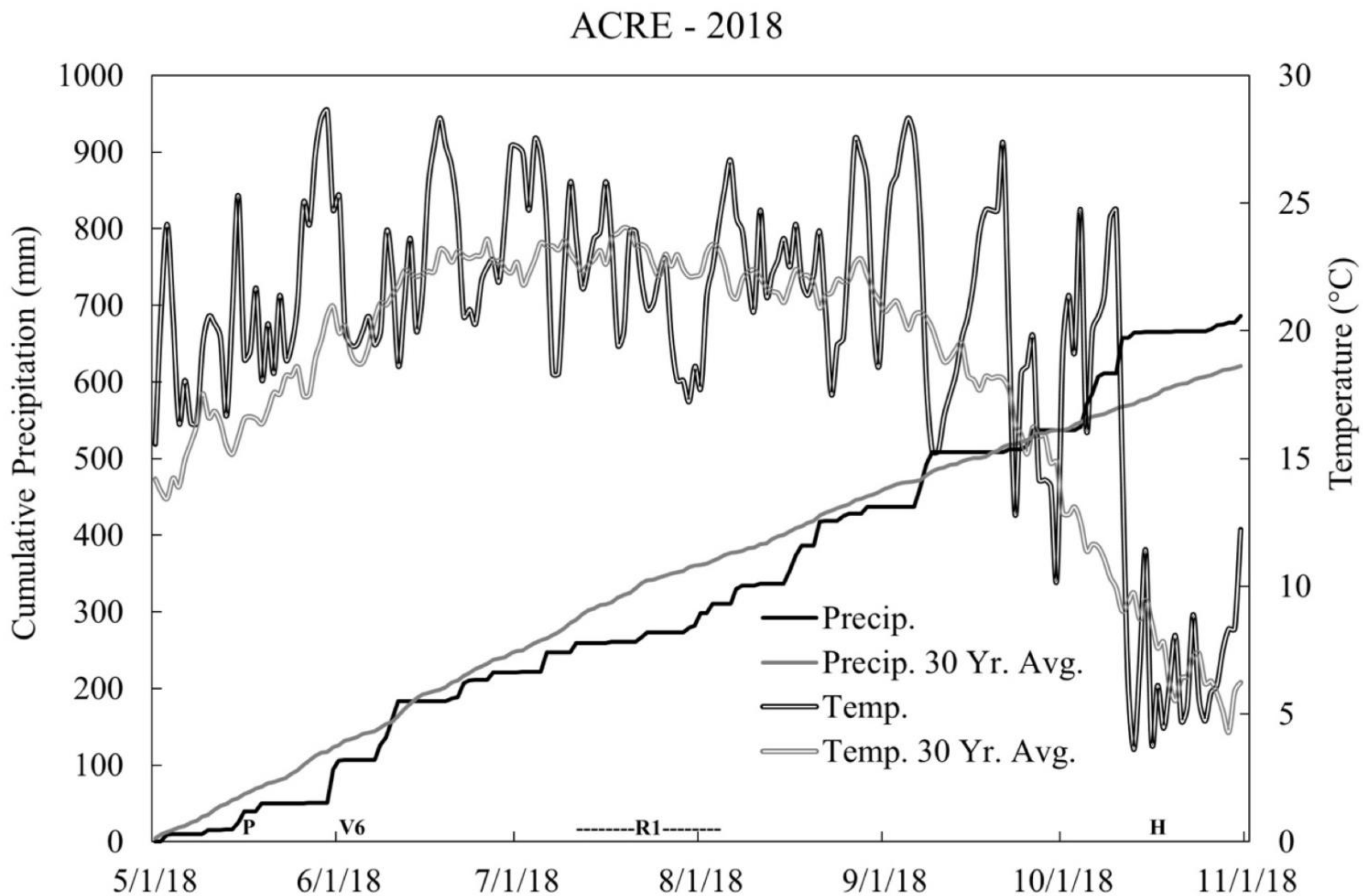

Figure A.2. Daily mean temperatures (°C) and precipitation (mm day$_{-1}$) during the 2018 growing season and the historic 30-year mean (1988-2017) at the Agronomy Center for Research and Education (ACRE) farm near West Lafayette, Indiana. Field activities are noted as; planting (P: 5/12), V5-V6 N application (V6: 6/5), 50% flowering (R1: ~7/18) and harvest (H: 9/28).

APPENDIX B. CHAPTER 3 – APPENDIX TABLES AND FIGURES

Table B.1. Mean soil fertility to 20cm for each replication (1 to 4) at the Mary S. Rice farm site in 2017 for pH, organic matter (OM), cation exchange capacity (CEC), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca).

	pH	OM	CEC	P	K	Mg	Ca
Replication		(%)	(cmol$_c$ kg^{-1})	——(mg kg^{-1})——		—(mg Mg^{-1})—	
1	6.3	3.1	8.9	70.0	183	283	970
2	6.1	2.7	7.6	78.0	150	252	778
3	5.5	2.2	6.8	80.0	129	164	541
4	6.1	2.4	7.7	71.0	176	224	835
Mean	**6.0**	**2.6**	**7.8**	**74.8**	**160**	**231**	**781**

Table B.2. Mean soil fertility to 20cm for each replication (1 to 5) at the Mary S. Rice farm site in 2018 for pH, organic matter (OM), cation exchange capacity (CEC), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca).

	pH	OM	CEC	P	K	Mg	Ca
Replication		(%)	(cmol$_c$ kg^{-1})	——(mg kg^{-1})——		—(mg Mg^{-1})—	
1	5.8	2.2	9.6	42.0	116	240	974
2	5.5	2.3	10.1	54.0	194	177	897
3	6.0	2.0	7.1	75.0	182	177	787
4	5.9	2.3	10	46.0	155	248	1013
5	6.0	2.1	8.1	55.0	169	220	925
Mean	**5.8**	**2.2**	**9.0**	**54.0**	**163**	**212**	**919**

Table B.3. Vegetative (V5 and V12 stage; before N application) and reproductive (R6 stage) soil nitrate (NO_3^-) and ammonia (NH_4^+) concentrations at two depths taken 20cm from the row in 2018 as affected by individual treatments. Different letters indicate a significant difference at p-value <0.05.

		V5 Stage				V12 Stage				R6 Stage			
Individual	Total N	0-30cm		30-60cm		0-30cm		30-60cm		0-30cm		30-60cm	
Treatment†	(kg N ha^{-1})	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+
Zero	26	10.1 **c**	3.2	4.5 **b**	3.1	--	--	--	--	5.2	5.6	5.2	6.0
AP_112	112	28.3 **b**	3.9	6.7 **ab**	3.3	--	--	--	--	4.8	5.0	4.2	4.6
AP_224	224	49.3 **a**	3.8	9.4 **a**	3.0	17.0 **a**	1.4	10.6	1.6	6.0	5.8	6.0	5.6
V5_str	202	31.9 **ab**	4.1	8.3 **a**	3.3	--	--	--	--	5.0	5.6	4.2	4.8
V5_inj	202	20.1 **b**	3.6	7.0 **ab**	3.2	--	--	--	--	4.8	4.6	4.4	5.0
V8_urea	202	29.0 **b**	4.7	7.3 **ab**	3.2	--	--	--	--	6.8	5.8	5.4	5.6
V12_str	202	--	--	--	--	7.0 **b**	1.6	7.0	2.2	5.8	5.8	4.4	5.0
V12_inj	202	--	--	--	--	10.2 **ab**	1.8	9.4	1.8	5.2	5.2	4.4	5.4

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha^{-1} as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha^{-1} (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).

Table B.4. Post V5 final plant population averaged across years (2017 and 2018) as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

Individual Treatment†	Total N (kg N ha^{-1})	Final Plant Population (plants ha^{-1})
Zero	26	69,300
AP_112	112	69,900
AP_224	224	70,000
V5_str	202	70,500
V5_inj	202	69,800
V8_urea	202	70,500
V12_str	202	70,200
V12_inj	202	69,500
	Mean	**70,000**
Sidedress UAN Treatment Groups		Level of Significance Pr > F
Placement‡		ns¶
Timing§		ns
Placement x Timing		ns

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha^{-1} as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha^{-1} (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).
‡Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)
§Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)
¶ns, nonsignificant at p<0.05 probability level

Table B.5. SPAD for 2017 and 2018 and leaf area index for 2018 as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

		SPAD					Leaf Area Index		
Individual	Total N	(V9)	(V12)	(V8)	(V12)	(R1)	(V12)	(R2)	(R4)
Treatment†	(kg N ha^{-1})	6/26/17	7/6/17	6/15/18	7/2/18	7/18/18	7/2/18	7/27/18	8/18/18
Zero	26	52.6	48.6	53.8 **b**	47.5 **b**	42.9 **b**	5.1	5.4	3.8
AP_112	112	55.2	47.1	57.0 **ab**	54.0 **a**	56.2 **a**	5.3	5.4	3.8
AP_224	224	53.1	50.3	56.9 **ab**	56.3 **a**	59.3 **a**	5.7	5.2	4.0
V5_str	202	55.5	49.0	58.2 **a**	55.1 **a**	62.2 **a**	5.5	5.4	4.5
V5_inj	202	55.2	50.5	56.4 **ab**	54.4 **a**	58.2 **a**	5.3	6.1	4.6
V8_urea	202	54.5	48.8	58.3 **a**	52.7 **a**	59.2 **a**	5.5	5.4	3.7
V12_str	202	52.1	48.4	57.3 **a**	53.6 **a**	60.1 **a**	5.3	5.4	3.8
V12_inj	202	54.7	48.0	58.8 **a**	53.3 **a**	57.5 **a**	5.6	5.4	3.9
Sidedress UAN Treatment Groups		Level of Significance Pr > F							
Placement‡		ns¶	ns	ns	ns	ns	ns	ns	ns
Timing§		*(V5)	ns	ns	ns	ns	ns	*(V5)	ns
Placement x Timing		ns	ns	ns	ns	ns	ns	ns	ns

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha^{-1} as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha^{-1} (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).
‡Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)
§Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)
¶ns, nonsignificant at p<0.05 probability level
*Significant at p<0.05 probability level

Table B.6. Cumulative growing degree days (GDD_c; base 10°C) from planting to reach 50% silk and tassel development and the anthesis silking interval (ASI; days) averaged across years (2017 and 2018) as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

Individual Treatment†	Total N (kg N ha^{-1})	Silking	Tassel	ASI
		——(GDD$_c$)——		—(± Days)—
		694	715	-1.8
Zero	26	694	707	-1.0
AP_112	112	700	723	-1.8
AP_224	224	688	715	-1.8
V5_str	202	694	715	-1.8
V5_inj	202	688	700	-1.1
V8_urea	202	688	715	-2.1
V12_str	202	688	715	-1.8
Sidedress UAN Treatment Groups		Level of Significance Pr > F		
Placement‡		ns¶	ns	ns
Timing§		ns	ns	ns
Placement x Timing		ns	ns	ns

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha^{-1} as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha^{-1} (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).

‡Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)

§Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)

¶ns, nonsignificant at p<0.05 probability level

Table B.7. Flowering (R1) earleaf nutrient concentrations for Ca and Mg, Mn, Fe, B, and Al averaged across years (2017 and 2018) as affected by individual and grouped treatments. Different letters indicate a significant difference at p-value <0.05.

Individual Treatment†	Total N (kg N ha-1)	Ca	Mg	Mn	Fe	B	Al
		(%)		(mg kg-1)			
Zero	26	0.25 **b**	0.21 **b**	24.8	96.0	1.88	31.3
AP_112	112	0.29 **ab**	0.26 **ab**	26.7	119.3	2.89	35.8
AP_224	224	0.33 **a**	0.29 **a**	32.1	128.4	2.00	46.0
V5_str	202	0.31 **ab**	0.28 **a**	32.7	125.4	2.44	44.9
V5_inj	202	0.31 **a**	0.25 **ab**	39.3	132.7	2.44	45.2
V8_urea	202	0.31 **a**	0.28 **ab**	40.0	121.1	1.89	40.0
V12_str	202	0.30 **ab**	0.25 **ab**	32.9	109.4	2.33	32.6
V12_inj	202	0.29 **ab**	0.26 **ab**	25.4	118.9	2.33	44.7
Sidedress UAN Treatment Groups		Level of Significance Pr > F					
Placement‡		ns¶	ns	ns	ns	ns	ns
Timing§		ns	ns	ns	ns	ns	ns
Placement x Timing		ns	ns	ns	ns	ns	ns

†Treatments include a single at-plant (AP) application at total N rates of 26 (Zero), 112 (AP_112), and 224 (AP_224) kg N ha-1 as urea ammonium nitrate (UAN) or split N applications receiving 202 kg N ha-1 (split 55:45 between AP and sidedress) as UAN at V5 or V12 where N was surface streamed (str) (V5_str and V12_str), subsurface injected (inj) (V5_inj and V12_inj), or broadcast applied as urea at V8 (V8_urea).
‡Placement (mean of V5_str + V12_str versus the mean of V5_inj + V12_inj)
§Timing (mean of V5_str + V5_inj versus the mean of V12_str + V12_inj)
¶ns, nonsignificant at p<0.05 probability level

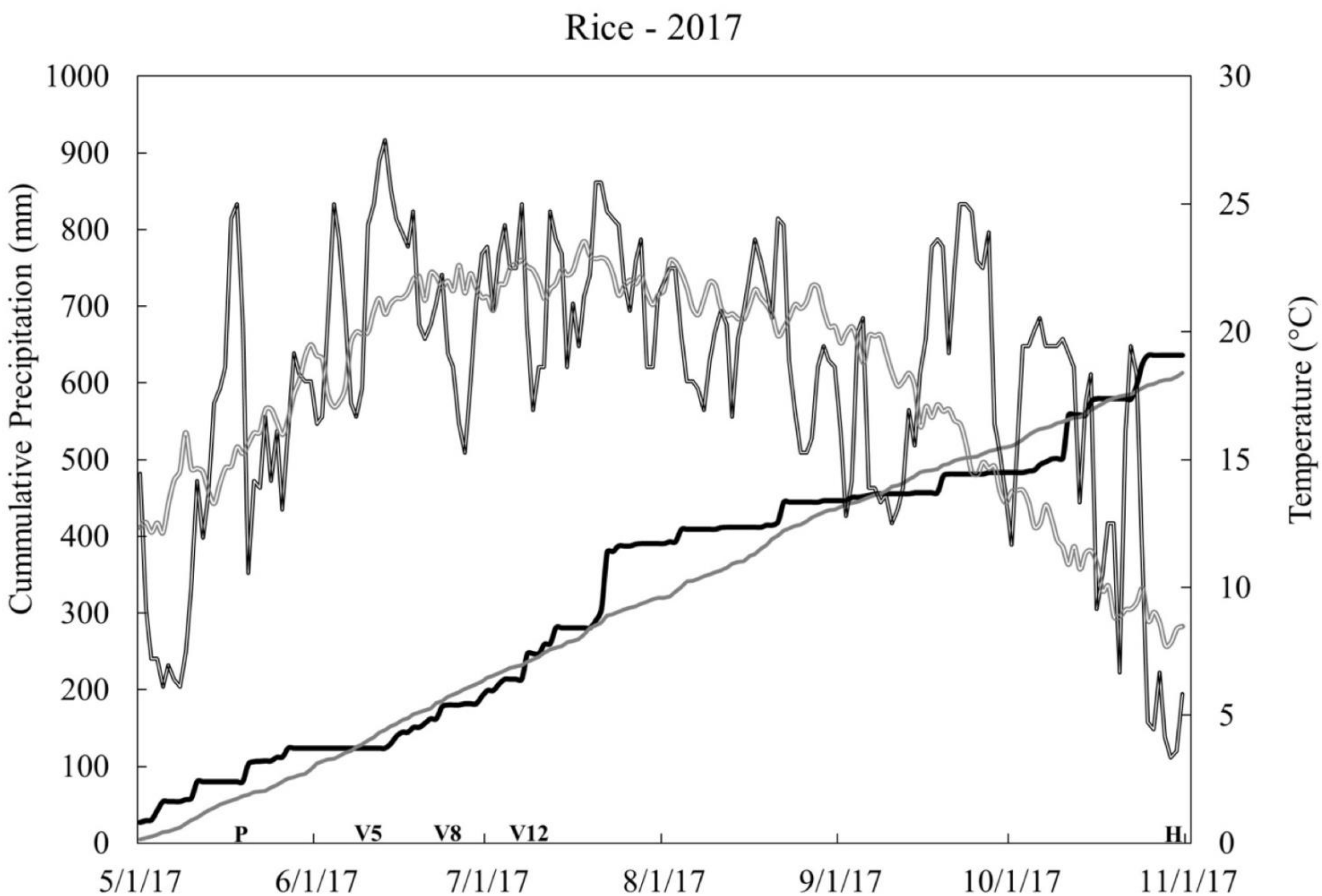

Figure B.1. Daily mean temperatures (°C) and precipitation (mm day-1) during the 2017 growing season and the historic 30-year mean (1988-2017) at the Mary S. Rice farm near La Crosse, Indiana. Field activities are noted as; planting (P: 5/16), V5 N application (V5: 6/16), V8 N application (V8: 6/22), V12 N application (V12: 7/6), and harvest (H: 11/1).

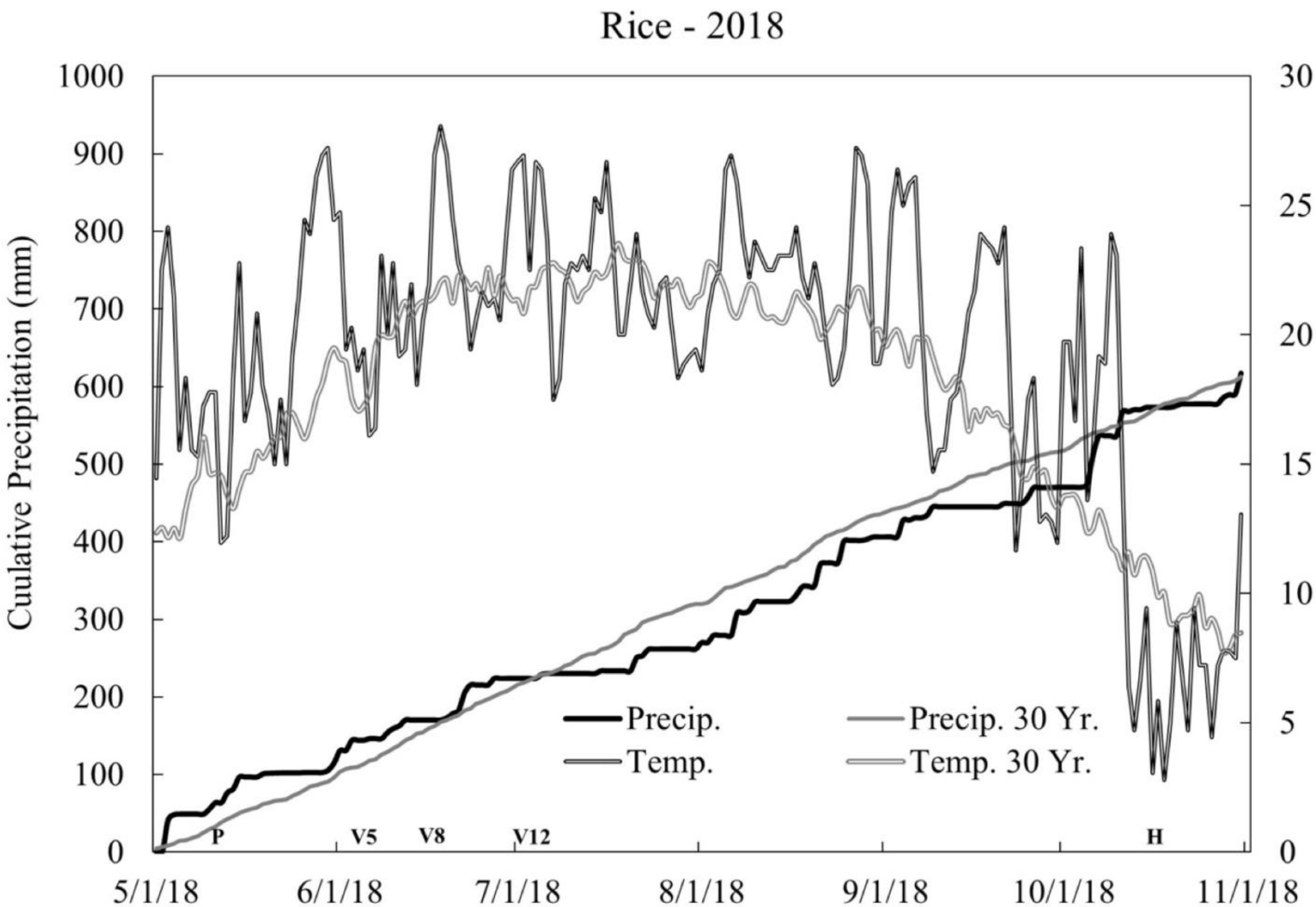

Figure B.2. Daily mean temperatures (°C) and precipitation (mm day^{-1}) during the 2018 growing season and the historic 30-year mean (1988-2017) at the Mary S. Rice farm near La Crosse, Indiana. Field activities are noted as; planting (P: 5/16), V5 N application (V5: 6/16), V8 N application (V8: 6/22), V12 N application (V12: 7/6), and harvest (H: 11/1).