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THE USE OF FERTILIZER NITROGEN APPLICATIONS TO INCREASE PRODUCTIVITY OF SOYBEAN

BY

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THESIS

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ABSTRACT

For optimal productivity, soybean [*Glycine max* (L.) Merr.] may require fertilizer nitrogen (N) to supplement biological N fixation. The objective of this study was to identify the best fertilizer source and the best plant growth stage for N applications to increase soybean yield using N fertilization. Trials were established at three locations in Illinois during three consecutive years for a total of nine site-years. In 2014, five different N sources were supplied and in 2015 and 2016, seven different N sources were supplied at one of four different soybean growth stages (preplant, V3, R1, and R3) at an application rate of 112 kg N ha^{-1} (100 lb N ac^{-1}). The seven different N sources evaluated were: ammonium nitrate (AN, 34-0-0), ammonium sulfate (21-0-0-24S), ESN (environmentally-smart nitrogen, 44-0-0), urea + Limus (urea treated with the urease inhibitor Limus, 46-0-0), liquid urea-ammonium nitrate (UAN, 28-0-0), urea (46-0-0), and a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate (30-0-7-2S), along with an unfertilized control. When averaged across all locations, significant increases in yield occurred when N was supplied during the early growth stages (preplant and V3) in 2014 and 2016. While in 2015, significant increases in yield were more apparent from N applications during the reproductive growth stages (R1 and R3). Fertilizing with AN or ESN at preplant produced the most consistent yield increases over the nine site-years. However, when examining the individual locations, variation in N source and the application time that gave the greatest yield increase was evident, suggesting that yield increases are dependent upon a given location, N source, and/or application time.

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LITERATURE REVIEW

Current Soybean Demand and Production

The current world population consists of 3.2 billion people and is expected to expand to over 9 billion by the year 2050 (United States Census Bureau, 2017). In order to meet the dietary demand of the future world population, crop yields will need to increase at least 2.4% each year, but unfortunately, they are only currently increasing at a rate of less than 1.7% each year (Ray et al, 2013). Because the amount of land that can be converted into production is limited, it becomes important for farmers to increase yields on land that is already being cultivated. Intensification of yield is also the optimal approach as it avoids the increase of greenhouse gas emissions and the disturbance of already-existing habitats (Edgerton, 2009). The production of soybean is invaluable because of the vast amount of uses for the crop. Most commonly, soybean meal is used as a protein source for livestock feed, while soybean oil is used as a cooking oil, as well as biodiesel. In less developed countries, such as Africa, soybean is even used as a flour and milk substitute.

In 2016, the United States harvested approximately 6.9 million Mg (83 million bu) of soybean (USDA-NASS, 2016). Illinois harvested the most soybean acres of any state in 2016, producing over 573 thousand Mg (9.8 million bu) alone (USDA-NASS, 2016). The average yield for Illinois is currently 3.05 Mg ha^{-1} (52.1 bu ac^{-1}) (USDA-NASS, 2017), with a new record yield for the state being set in 2015 consisting of 6.34 Mg ha^{-1} (108.3 bu ac^{-1}) (Illinois Soybean Association, 2015). Such a record indicates that doubling or tripling current soybean yields are not impossible, and allow those involved in agriculture to strive towards reaching the same yield goals. Those farmers who participate in yield contests, often adopt forward-thinking management practices. Determining the best agronomic practices for growers to increase yields, while remaining economical during the time of a volatile grain market, is not easy, but is ultimately the best strategy for increasing yields to feed the growing population.

Soybean Nodulation

Like most other legumes, the soybean plant utilizes a symbiotic relationship to obtain nitrogen (N) through biological N fixation (BNF). Even though the atmosphere is made up of 79% nitrogen gas (N_2), the soybean plant can only benefit from this nutrient source if the *Bradyrhizobium japonicum* bacteria are present in the soil and nodulation occurs (Conley and Christmas, 2005). The symbiotic relationship is characterized by nodules that are formed through an infection process beginning with the *Bradyrhizobium japonicum* bacteria, more commonly referred to as rhizobia, becoming attached to a curling soybean root hair (Taiz and Zeiger, 1998). The rhizobia will then penetrate the wall of the root hair and are transported through an infection thread to the root cells (Taiz and Zeiger, 1998). From this point, the root cells will divide, allowing the formation of nodules. The rhizobia use nitrogenase enzymes to convert nitrogen gas (N_2) from the atmosphere into ammonia (NH_3) in the nodules, which is quickly converted into organic forms of N to avoid plant toxicity (Taiz and Zeiger, 1998). These organic forms of N are allantoin, allantoic acid, and citrulline, which are collectively known as ureides. The ureides are then moved from the nodules to the shoot through the plant xylem (Taiz and Zeiger, 1998).

Approximately 10 to 14 days after rhizobia infection, nodules on the soybean root are visually apparent and will expand in size until beginning BNF between the V2 and V3 soybean growth stage (Conley and Christmas, 2005). Nodules that are actively undergoing BNF will appear red, pink, or orange in color. These colors are due to the presence of leghemoglobin, which contain the same iron-binding compound found in human blood. The level of gas permeability that the nodules possess is controlled by the soybean plant (Taiz and Zeiger, 1998).

The nodules must maintain adequate oxygen levels for respiration to occur, as excess oxygen will inhibit nitrogenase activity. Exposure to drought conditions or increased soil nitrate (NO_3^-) levels decrease the permeability of the nodule surface, therefore reducing the already small amount of oxygen found inside the nodule, resulting in poor BNF (Taiz and Zeiger, 1998). Therefore, although a well-established rhizobia population may be present in the soil, environmental conditions can still have a major impact on BNF and therefore affect yield (Gascho, 1993).

Near the end of the growing season, nodules will cease BNF and slough off (Garcia and Hanway, 1976). At this point, root growth will also stop and the uptake of nutrients will slow (Garcia and Hanway, 1976). Nutrients are then translocated from the vegetative plant tissues to the seed, which in turn decrease the rate of photosynthesis to the leaves resulting in the soybean leaves turning yellow in color and detaching from the plant (Garcia and Hanway, 1976).

Nitrogen Utilization in Soybean

In general, soybean requires a large amount of N due to its high protein concentration of the seed (Sinclair and de Wit, 1976). The majority of the N will accumulate in the soybean seed during seed-fill, and as much as 95% of the total plant N can be found in the seeds at harvest (Gascho, 1993). Soybean is unique in nature due to the fact that it needs a high amount of N, but yet produces biomass at one of the slowest rates of all row crops. When observing the N uptake patterns of soybean, Bender et al. (2015) noted that a 3.6 Mg ha^{-1} (60 bu ac^{-1}) soybean crop requires at least 268.8 kg ha^{-1} (240 lb ac^{-1}) of N per acre during the growing season. For such a high amount of N to be obtained over the entire growing season, the plant must accumulate at least 4.5 to 5.6 kg ha^{-1} (4 to 5 lb ac^{-1}) of N per day. Although, 50 to 60% of this amount of N can come from the nodules (Salvagiotti et al., 2008), mineralization and residual N fertilizer alone will unlikely be able to supply the remaining 50% of the N needed by higher-yielding soybean.

While a steady supply of N is needed by the soybean plant over the entire growing season, N uptake increases as the plant reaches its reproductive stages (Bender et al., 2015). To maximize soybean yield, the crop must be able to maintain high photosynthetic rates and concurrently accumulate a large amount of N in the seeds (Salvagiotti et al., 2008). Since maximum BNF takes place between the R3 and R5 soybean growth stages (Zapata et al., 1987), it is important for the plant to have an adequate supply of N lasting through reproductive growth. If the amount N is limited during the soybean growing season, it will be remobilized from the leaves to the seed, resulting in earlier senescence. Sinclair and de Wit (1976) determined that soybeans are “self-destructive” meaning that the translocation of N due to an N deficiency could potentially shorten the seed developmental period and therefore decrease seed number, and that the length of the seed filling period was ultimately more important than the rate of seed fill. Consequently, either increasing the N supply to the roots or increasing the stored N within the soybean plant may ultimately increase yield (Sinclair and de Wit, 1976).

Nitrogen Sources

When it comes to nitrogen, plants are able to use either ammonium (NH_4^+) or nitrate forms (Aldrich, 1980b). Although, ammonium and nitrate fertilizers are both commonly used in production agriculture, the two ions behave differently. Since ammonium is a cation, it is attracted to the soil and cannot be leached nor does it move through the soil with water (Aldrich, 1980a). However, ammonium can be transformed into ammonia that is easily lost into the atmosphere through volatilization. Anhydrous ammonia is the most common N source used in the United States, because it is the easiest source to manufacture and therefore, the cheapest N source for growers. However, since it is in the form of a gas, additional labor and caution must be executed as the liquefied gas must be injected into the ground to prevent its escape into the atmosphere.

Nitrate is an anion that is repelled from the soil and can be transported with water movement through the soil (Aldrich, 1980a). Thus, nitrate is subject to leaching and can be easily lost under suitable environmental conditions. On the contrary, because nitrate can move so freely in the soil, it is the easiest source of N for plant uptake (Aldrich, 1980a). Nitrate sources are commonly used in production agriculture despite the negative environmental threats they might pose. Denitrification is another major process where N can be lost. Some of the bacteria living in the soil can flourish in the absence of air by obtaining their oxygen supply from the oxygen found in nitrate (Aldrich, 1980a). Because of this, the denitrification process is often accelerated when the soil is saturated, contains a large amount of undecomposed plant tissues, or has a large amount of nitrate (Aldrich, 1980a). Under these conditions, the bacteria can convert nitrate to nitrogen gas thereby allowing N to escape into the atmosphere (Aldrich, 1980a).

Urea is the only N fertilizer source that doesn’t carry a negative or positive charge (Aldrich, 1980a). However, after application to the soil, urea is quickly converted to ammonium by the urease enzyme (which can be freely present in soil), resulting in the urea fertilizer source having the same the properties as other ammonium fertilizers and notably having the ability to easily volatilize into the atmosphere (Aldrich, 1980a). The amount of time that it takes volatilization to occur is dependent on the rate of urea hydrolysis. Urea hydrolysis is a set of chemical reactions that eventually transforms urea into ammonia. Weather conditions that favor volatilization are high temperatures because warm soil lacks the ability to retain ammonia gas, as well as increased soil moisture levels as it causes the ammonia to be left in solution (Jones et al., 2013).

Nitrogen-Loss Inhibitors

Since N has the greatest ability of all of the nutrients to be lost from the soil (Hoeft, 1984), the use of N-loss inhibitors has become popular in the agricultural sector. Such developments to minimize N-loss are dictated by environmental concern, as well as high fertilizer prices. Most of the N-loss inhibitor products developed work by preventing changes in N form that can result in N-loss (Fernández et al., 2009).

Denitrification and leaching are the most common processes, and are of greatest concern for soil N-loss (Hoeft, 1984). Both of these processes take place under very wet soil conditions (Hoeft, 1984). Denitrification consists of the reduction of nitrate to nitrite (NO_2^-) to gaseous forms of N, while leaching is simply the profile movement of N with soil water away from the crop. Leaching is often more of a concern, since nitrate is water-soluble and can easily flow with soil water and eventually end up in surface and ground waters.

Nitrification inhibitors slow down the conversion of ammonium to nitrate by inhibiting the activity of *Nitrosomonas* bacteria (Hoeft, 1984). Common names of such products are dicyandiamide (DCD) and nitrapyrin. Yield increases of 0.53 to 1.59 Mg ha^{-1} (10 to 30 bu ac^{-1}) can be obtained in corn from the use of a nitrification inhibitor during growing seasons that receive an increased amount of precipitation (Fernández et al., 2009). However, the same yield increases from nitrification inhibitors will likely not exist in years when the soil is too dry (Fernández et al., 2009).

Urease inhibitors contain a chemical known as N-(n-butyl) thiophosphoric triamide (NBPT) (Fernández et al., 2009). This NBPT inhibits the conversion of urea to ammonia. Over the last several years, corn trials across the Midwest have shown an average yield increase of 0.23 Mg ha^{-1} (4.3 bushels ac^{-1}) when NBPT is added to urea and 0.09 Mg ha^{-1} (1.6 bu ac^{-1}) when NBPT is applied with UAN solutions (Fernández et al., 2009). In a year with particularly dry environmental conditions, the use of a urease inhibitor has increased yield as much as 1.63 Mg ha^{-1} (20 bu ac^{-1}) (Fernández et al., 2009).

Urea is also available as a fertilizer with a polymer-coating that allows for its slow-release over an extended period of the growing season. The coating is meant to act as a protectant against volatilization, which occurs as urea is transformed into ammonium shortly after application. The rate at which the N is released from the polymer-coating is dependent on both temperature and moisture (Fernández et al., 2009). During years of increased rainfall early in the growing season, slow-release products can protect urea from being lost by denitrification and leaching as well (Fernández et al., 2009).

Further research is needed to determine the efficiency and economic value of these N-loss inhibitor products. Hoeft (1984) reported that the benefits from the use of N-loss inhibitors are more likely to be noticed when there is more time between fertilizer application and crop need. Nitrogen-loss inhibitors give producers the ability to apply N when it is most convenient for their operation. Therefore, the efficiency of fall and early spring applications of N may be increased with the use of N-loss inhibitors.

Nitrogen Applications on Soybean

Past studies have often shown inconsistent physiological results when N fertilizer has been supplied to the soybean crop. Notably, increased amounts of nitrate in the soil, as well as N fertilization, often inhibit nodule formation, nodule number, and reduce BNF (Gibson and Harper, 1985; Lyons and Earley, 1952). The rationale behind these findings is still uncertain, but nitrate may simply lower the carbon to nitrogen ratio of the nodules (Harper and Cooper, 1971). More recently, Fujikake et al. (2003) discovered that excessive nitrate levels caused a decrease in the supply of carbohydrates to the nodules, suggesting that supplied nitrate may increase the sink strength of the roots and that more photoassimilate will be partitioned to the roots instead of the nodules.

Urea might be a better N source for fertilizing soybean than ammonium or nitrate sources, since a portion of this N source may be able to be metabolized directly by the soybean plant and transported through the shoot as ureides (McNeil and LaRue, 1983). If the plant takes up N in the form of ureide, rather than ammonium or nitrate, nodulation and BNF may not be as greatly inhibited by the extra N in the soil. In a study using soybeans grown hydroponically, nodulation was drastically reduced with as little as 3 mM of nitrate-N, but hardly affected by 18 mM of urea-N (Virgue et al., 1977). However, such results may not be as noticeable in a field situation, since some urea is eventually converted to nitrate.

The best growth stage to apply fertilizer N to soybean remains somewhat uncertain. Because the soybean N uptake curve shows an increased amount of N is needed by the soybean plant as it approaches the reproductive growth stages, the optimal time to apply N may be during these early reproductive stages (Bender et al., 2015). However, since applying late-season N to the soybean crop is not mechanically practicable due to canopy closure between rows, it has been strategized that an early-supplied controlled-release N source could be utilized later in the growing season by the soybean plant, or N fertilizer could be placed below-ground past the nodulation zone. Harper and Cooper (1971) supplied 150 ppm of AN both on top of the soil and 30.5 cm below the ground, and noted that nodule fresh weight and leghemoglobin was reduced more by the above-ground treatment. The deep placement of the AN not only resulted in better nodulation, but greater nitrate uptake as well. In China, the deep placement of slow-release urea in converted rice paddies significantly increased soybean yield when compared to a broadcast application of slow-release urea (Takahashi et al., 1991). The deep placement treatment also decreased N fixation far less than the broadcast application. In contrast, Takahashi et al. (1992) described that such deep placement resulted in poor nitrification, and that the same yield increases might be possible with the deep placement of less expensive, non-coated N sources. Similar results were also discovered by Salvagiotti et al. (2009), when an application of deep banded slow-release urea resulted in almost the same level of BNF as the unfertilized control, but did not lead to an increase in seed yield as did the broadcast applications of AN.

In settings that use irrigation, supplying late-season N is not a problem. As irrigated soybeans can often yield more than non-irrigated soybeans, this type of environment could more easily utilize and benefit from supplemental N. In Kansas, six out of eight soybean sites responded to irrigated N applications with an average yield increase of 0.40 Mg ha^{-1} (6.9 bu ac^{-1}) when supplied at the R3 growth stage (Wesley et al., 1998). Another site in Georgia on particularly sandy soils showed yield responses of 0.35 to 0.53 Mg ha^{-1} (6 to 9 bu ac^{-1}) when N was irrigated, dribbled down the row, or used as a foliar application during the R3 to R5 soybean growth stages (Gascho, 1993). The same study also showed positive results when N was applied using the same three application methods in combination with boron. While supplying nutrients via irrigation may be an easy and worth-while practice, the majority of soybeans in the United States are grown on acres where adequate rainfall almost always occurs, and does not necessitate the need for irrigation systems, limiting the potential of this technique.

While soil application is the most common form of field crop fertilization, foliar applications are another relatively easy way to apply N during late-season stages of soybean growth. Such sprays are commonly tank-mixed during insecticide and fungicide applications, making it an opportune time to supply foliar fertilizer as well. However, yield increases from the use of foliar N applications only intermittently occur. Yield increases of 0.91 Mg ha^{-1} (15.5 bu ac^{-1}) were obtained when a foliar spray of N + P + K + S was applied four times throughout the soybean reproductive growth stages (Garcia and Hanway, 1976). Multiple applications of small rates were used in order to avoid the leaf burn sometimes associated with a single application of larger rates of foliar fertilizer. However, numerous application times would be challenging for growers to accomplish. Unfortunately, other studies with less application times have failed to obtain the degree of yield response as did Garcia and Hanway (1976).

Low rates of N fertilizer applied at planting have also produced positive yield increases in soybean. In eastern South Dakota, supplying 16 kg N ha^{-1} (14.3 lb N ac^{-1}) AN and urea placed as a 5 x 5 band (5 cm down and 5 cm to the side of the seed) at planting produced a yield increase of 6% due to increases in both plant biomass and plant N (Osbourne and Riedell, 2006). Thus, an early season application of N on soybean, may provide a supply of N before nodules have formed. Moreover, an application of N at planting may be utilized by the soybean plant before nodule formation begins, thereby decreasing the supplemental N level in time to avoid nodule inhibition. In a double-cropping system near the Gulf Coast, soybean planted in July after the harvest of full-season corn responded to 50 kg N ha^{-1} (44.65 lb N ac^{-1}) by a yield increase of 0.15 Mg ha^{-1} (2.56 bu ac^{-1}) (Starling et al., 1998). Since yield reductions are common in double-cropping systems, supplying late-planted soybean with N might increase vegetative growth, which in turn could increase yield (Starling et al., 1998).

Since many N applications on soybeans have shown inconclusive results, it is likely that environmental factors such as temperature and moisture play a major role. During a particularly dry growing season a plow-down application of as little as 112 kg ha^{-1} (100 lb ac^{-1}) of AN produced large yield increases, while during a growing season with adequate rainfall, plow-down applications of AN up to 1,120 kg ha^{-1} (1,000 lb ac^{-1}) only resulted in minor yield increase (Lyons and Earley, 1952). Therefore, specific growing season temperatures and rainfall will influence BNF, which indirectly affects the soybean yield response to supplemental N (Lyons and Earley, 1952).

INTRODUCTION

While genetic and management practices (i.e. narrow rows, earlier planting) of soybean have improved, one additional factor likely preventing maximum yields is inadequate fertility. Traditionally, soybean has largely been thought of as only a rotational crop, and not as a crop that needs additional nutrient inputs, especially in regards to N. Moreover, the so-called "soybean N credit" concept has existed among growers for years and has often led to the idea that the soybean plant produces more N than it can use and that residual N is leftover for the next season's corn crop. This misconception has also at times contributed to a decrease in the amount of N fertilizer supplied to a corn crop following soybean. However, recent findings suggest that soybean is only able to fix about half of its total N requirement (Salvagiotti et al., 2008), with the remainder having to come from either mineralization of soil organic matter, residual N fertilizer left over from the previous corn crop, or N fertilizer supplied specifically for the soybean crop.

Even though contemporary publications have concluded that soybean needs more N than the soil and nodules can provide, studies regarding supplemental N applications have shown unpredictable results. In a meta-analysis of 108 studies conducted by Salvagiotti et al. (2008), half of the sites included in the analysis responded to fertilizer N applications. Of the sites that responded, the average response was 0.47 Mg ha^{-1} (8 bu ac^{-1}). The important phenomenon of why soybean sometimes responds at certain locations to different N application timings, rates, and sources needs to be further investigated. The objective of this research is to provide knowledge of the most appropriate N fertilizer source and application growth stage to increase soybean yield. To accomplish this, numerous N sources were supplied at one of four different soybean growth stages during three consecutive growing seasons at three different locations in Illinois each year.

MATERIALS AND METHODS

Location

To obtain a variety of soil types and weather patterns, locations in northern, central, and southern Illinois were chosen each year in 2014, 2015, and 2016. In all cases, corn was the previous crop and conventional tillage was used. The drainage and topography of each site are optimal with good water holding capacity. Preplant soil measurements for organic matter, pH, and mineral composition (using Mehlich-3 extraction) were obtained by sampling to a depth of 15 centimeters in 2014 and 30 centimeters in 2015 and 2016 (Table 1). In 2014 and 2015, site locations included DeKalb, Champaign, and Harrisburg. In 2016, sites were located at Yorkville, Champaign, and Harrisburg (Table 1).

Agronomic Management

In 2014 and 2015, the FS *HiSoy* soybean varieties FS 31-A32, FS 39-A42, and FS 42-A12 and in 2016, FS 32-A50, FS 39-A42, and FS 42-A12 were selected based on maturity group for each location. In 2014, plots were planted on 20 May in DeKalb, 27 May in Champaign, and 24 May in Harrisburg. In 2015, plots were planted on 21 May in DeKalb, 23 May in Champaign, and 3 May in Harrisburg. In 2016, plots were planted on 19 May at Yorkville, 22 May in Champaign, and 5 May in Harrisburg. During all years, seed was planted to target a final population of 395,360 plants ha^{-1} (160,000 plants ac^{-1}) for all locations using an ALMACO Seed-Pro 360 planter (ALMACO, Nevada, IA). The plots were four rows wide, 11 meters in length with 0.76 meter row spacing. The treatments were arranged in a randomized complete block design and replicated six times at each location. Weed control consisted of a pre-emergence application of Boundary (Syngenta, Greensboro, NC) at a rate of 2.3 L ha^{-1} (2 pints ac^{-1}) for all years and locations. A post-emergence application of Touchdown (Syngenta, Greensboro, NC) at a rate of 3.5 L ha^{-1} (48 oz ac^{-1}) and Select Max (Valent, Walnut Creek, CA) 0.7 L ha^{-1} (9 oz ac^{-1})

was used for all locations in 2014. In 2015, a post-emergence application of Flexstar GT (Syngenta, Greensboro, NC) at a rate of 4.1 L ha^{-1} (3.5 pints ac^{-1}) and MSO (Loveland Products, Inc., Greeley, CO) at a rate of 0.9 L ha^{-1} (0.1 gal ac^{-1}) was used in DeKalb and Harrisburg, and a post-emergence application of Touchdown at a rate of 2.6 L ha^{-1} (35 oz ac^{-1}), AMS-Supreme (Drexel, Memphis, TN) at a rate of 1.9 L ha^{-1} (0.2 gal ac^{-1}), and InterLock (WinField United, St. Paul, MN) at a rate of 0.03 L ha^{-1} (0.4 oz ac^{-1}) were used in Champaign. In 2016, a post-emergence application of Flexstar (Syngenta, Greensboro, NC) at a rate of 4.1 L ha^{-1} (3.5 pints ac^{-1}) and MSO at a rate of 1.9 L ha^{-1} (0.2 gal ac^{-1}) were used at Yorkville. A post-emergence application of Flexstar at a rate of 4.1 L ha^{-1} (3.5 pints ac^{-1}), Roundup (Monsanto, St. Louis, MO) at a rate of 0.6 L ha^{-1} (8 oz ac^{-1}), MSO at a rate of 1.9 L ha^{-1} (0.2 gal ac^{-1}), and MasterLock (WinField United, St. Paul, MN) at a rate of 0.5 L ha^{-1} (6.4 oz ac^{-1}) were used at Champaign in 2016. A post-emergence application of Roundup at a rate of 2.3 L ha^{-1} (32 oz ac^{-1}), and MSO at a rate of 1.9 L ha^{-1} (0.2 gal ac^{-1}) was used at Harrisburg in 2016. Fungicide and insecticide applications were made during all years at all locations at the R3 plant growth stage. In 2014, all locations received an application of Priaxor (BASF, Florham Park, NJ) at a rate of 0.6 L ha^{-1} (8 oz ac^{-1}) and Fastac (BASF, Florham Park, NJ) at a rate of 0.3 L ha^{-1} (3.8 oz ac^{-1}). In 2015, all locations received an application of Priaxor at a rate of 0.6 L ha^{-1} (8 oz ac^{-1}), Fastac at a rate of 0.3 L ha^{-1} (3.8 oz ac^{-1}), and MasterLock at a rate of 0.5 L ha^{-1} (6.4 oz ac^{-1}). In 2016, all locations received an application of Quadris Top SBX (Syngenta, Greensboro, NC) at a rate of 0.5 L ha^{-1} (7 oz ac^{-1}), Endigo (Syngenta, Greensboro, NC) at a rate of 0.3 L ha^{-1} (3.5 oz ac^{-1}), and NIS (Red River Specialties, Inc., Shreveport, LA) at a rate of 0.2 L ha^{-1} (3.2 oz ac^{-1}).

Nitrogen Applications

In 2014, five N sources were evaluated: Ammonium Nitrate (AN, 34-0-0); Ammonium Sulfate (AMS, 21-0-0-24S); liquid Urea-Ammonium Nitrate (UAN, 28-0-0); Urea (46-0-0); ESN (44-0-0, controlled release polymer-coated urea, Agrium U.S., Inc., Denver, CO); along with an unfertilized control. In 2015 and 2016 two additional N sources were added: Urea + Limus (46-0-0, urea treated with the urease inhibitor Limus, BASF, Florham Park, NJ); and a mixture of Ammonium Nitrate + Potassium Nitrate + Ammonium Sulfate (30-0-7-2S). During all years, each source was supplied at one of four soybean growth stages consisting of preplant, V3, R1, or R3 (Table 2). In 2014, the preplant applications of granular sources were supplied using a spinner-spreader and were lightly incorporated using a harrow. In 2015 and 2016, the granular sources were broadcast supplied by hand and were not incorporated. During all years, the liquid UAN source was diluted and dripped down the center between two rows. All sources were supplied at 112 kg of N ha^{-1} (100 lb of N ac^{-1}). The two middle rows received the full N treatments and the outer two rows were used to provide a border.

Root Assessments

In 2014, soybean plant roots were assessed using two different methods for quantitative and qualitative nodule development. Three soybean plants from the center two rows of each plot at all three trial locations were sampled at the R4 plant growth stage. Nodule number was calculated based on a rating scale of 0 to 3. A score of 0 indicated that no nodules were present, 1 indicated that nodules were present on the taproot only, 2 indicated that nodules were present on the taproot and 1 to 3 lateral roots, and 3 indicated that nodules were present on the taproot and 4 or more lateral roots. To assess nodule color, 10 nodules on the same three soybean plants previously sampled were cut open using a fine razor. The pink hue occurring on the inside of each nodule was evaluated as an indirect measurement of leghemoglobin and nitrogenase activity. The pink hue was calculated based on a visual rating scale of 0 to 100%. Nodules with a brighter hue of pink would be rated with a higher percentage, meaning that a greater amount of nitrogenase activity was occurring inside the nodule.

Grain Yield

The center two rows of each plot were harvested for yield, yield components, and grain quality. Trials were harvested using an ALMACO SPC-40 combine (ALMACO, Nevada, IA) on 9 October in DeKalb, 14 October in Champaign, and 21 October in Harrisburg in 2014, on 16 October in DeKalb, 10 November in Champaign, and 2 October in Harrisburg in 2015, and on 18 October in Yorkville, 23 October in Champaign, and 5 October in Harrisburg in 2016. The combine is equipped with HarvestMaster GrainGage system (Juniper Systems, Logan, UT) to provide grain weight and moisture directly to an in-cab mounted Allegro MX field computer (Juniper Systems, Logan, UT). Subsamples of the grain were analyzed for grain quality (oil and protein) by NIT using a Foss Infratec 1241 grain analyzer (Eden Prairie, WI). The subsamples of grain were also used to estimate average individual seed weight based on a random subsample of 300 seeds (Old Mill 850-2, San Antonio, TX). Seed number was estimated by dividing the total plot grain weight by the average individual seed weight. Grain yield was standardized to both Mg ha^{-1} and bu ac^{-1}. Grain yields in Mg ha^{-1} and individual kernel weights are presented at 0% moisture, while grain yields in bu ac^{-1} are presented at 13% moisture.

Statistical Analysis

Statistical analysis for grain yield, yield components, grain quality, and nodule ratings were performed using PROC MIXED of SAS (SAS 9.4; SAS Institute Incorporated, Cary, NC). The years were analyzed both individually and together. PROC UNIVARIATE was used to evaluate the normality of the residuals and to remove potential outliers. LSD values were determined using the PDIFF macro with $\alpha = 0.10$ as the level of probability.

TABLES

Table 1. Pre-planting soil properties for three Illinois locations in 2014, 2015, and 2016. Soil tests were conducted to assess baseline soil fertility at a depth of 0 to 15 cm in 2014 and a depth of 0 to 30 cm in 2015 and 2016. Values are the average of six replications at each location.

Location	Soil Series	OM	CEC	pH	NO_3^-	NH_4^+	P	K	Ca	Mg
		%	meq $100g^{-1}$		---------------------- ppm --------------------					
2014										
DeKalb	Drummer-Elburn	4.5	18.4	6.7	-	-	20	113	2344	625
Champaign	Drummer-Flanagan	3.8	20.0	6.3	-	-	36	191	2532	535
Harrisburg	Patton-Harco	3.8	15.0	6.4	-	-	18	101	2305	245
2015										
DeKalb	Flanagan-Drummer	4.5	21	6.3	18	3.8	18	111	2692	722
Champaign	Flanagan-Drummer	3.5	17	6.3	20	2.7	38	139	2191	402
Harrisburg	Reesville-Patton	2.9	20	6.1	7	3.7	19	135	2516	486
2016										
Yorkville	Drummer-Milford	6.8	28.2	6.3	32.5	7.8	31	208	3447	822
Champaign	Flanagan-Drummer	3.0	19.0	6.6	6.1	5.7	26	127	2651	467
Harrisburg	Patton-Darwin	2.4	22.8	6.0	31.8	7.6	35	175	2687	591

Table 2. Dates of the N source fertilizer applications to soybean for each of the three Illinois locations in 2014, 2015, and 2016.

	Soybean growth stage at time of N application			
Location	**Preplant**	**V3**	**R1**	**R3**
2014				
DeKalb	May 20th	June 17th	July 2nd	July 23rd
Champaign	May 27th	June 18th	July 11th	July 22nd
Harrisburg	May 24th	June 25th	July 11th	July 18th
2015				
DeKalb	May 21st	June 26th	July 9th	July 30th
Champaign	May 22nd	June 22nd	July 2nd	July 23rd
Harrisburg	May 2nd	June 9th	June 25th	July 11th
2016				
Yorkville	May 22nd	June 21st	July 7th	July 21st
Champaign	May 20th	June 20th	July 8th	July 22nd
Harrisburg	May 4th	June 10th	June 30th	July 15th

Table 3. Monthly weather data between 1 April and 30 September for northern, central, and southern Illinois in 2014, 2015, and 2016. Temperature is the average daily air temperature and precipitation is the average monthly accumulated rainfall. Values were obtained from Illinois State Water Survey (1990-2010) and values in parentheses are the deviations from the 20-year average.

	Month					
Year	**April**	**May**	**June**	**July**	**August**	**September**
			Northern, IL†			
2014						
Temperature, °C	9.2 (-0.8)	15.7 (+0.1)	21.6 (+0.3)	20.6 (-2.5)	22.7 (+0.2)	17.3 (-1.0)
Precipitation, cm	8.2 (-1.4)	13.6 (+2.9)	20.7 (+10.8)	12.2 (+1.5)	14.8 (+4.6)	7.3 (-1.3)
2015						
Temperature, °C	10.4 (+0.4)	16.5 (+0.9)	19.9 (-1.4)	22.1 (-1.0)	21.6 (-0.9)	20.6 (+2.3)
Precipitation, cm	9.6 (+0.0)	11.4 (+0.7)	20.2 (+10.3)	9.5 (-1.2)	8.0 (-2.2)	8.1 (-0.5)
2016						
Temperature, °C	9.2 (0.8)	15.3 (-0.3)	21.7 (+0.4)	23.5 (+0.4)	23.9 (+1.4)	19.8 (+1.5)
Precipitation, cm	6.7 (-2.9)	23.5 (+12.8)	10.3 (+0.4)	19.5 (+8.8)	9.4 (-0.8)	4.8 (-3.8)
			Central, IL			
2014						
Temperature, °C	11.5 (+0.1)	17.7 (+0.7)	22.8 (+0.5)	21.0 (-2.7)	23.0 (-0.1)	18.1 (-1.1)
Precipitation, cm	10.0 (+0.9)	11.1 (-1.8)	20.9 (+10.1)	22.1 (+9.9)	3.9 (-6.0)	8.7 (+0.7)
2015						
Temperature, °C	12.1 (+0.7)	18.6 (+1.6)	22.2 (-0.1)	23.0 (-0.7)	22.1 (-1.0)	21.0 (+1.8)
Precipitation, cm	9.2 (+0.1)	15.4 (+2.5)	23.3 (+12.5)	10.7 (-1.5)	8.0 (-1.9)	16.4 (8.4)
2016						
Temperature, °C	11.4 (0.0)	16.6 (-0.4)	23.3 (+1.0)	23.9 (+0.2)	24.4 (+1.3)	21.0 (+1.9)
Precipitation, cm	8.3 (-0.8)	9.6 (-3.3)	18.1 (+7.3)	11.3 (-0.9)	10.5 (+0.6)	14.0 (+6.0)
			Southern, IL			
2014						
Temperature, °C	14.2 (+0.3)	18.6 (-0.5)	18.7 (+5.1)	25.5 (-3.1)	25.1 (-0.7)	20.8 (-1.8)
Precipitation, cm	19.8 (+8.3)	15.3 (+3.3)	11.5 (0.0)	5.9 (-2.6)	6.5 (-1.3)	1.9 (-5.8)
2015						
Temperature, °C	14.9 (+1.0)	19.4 (+0.3)	18.7 (+5.5)	25.5 (+0.3)	25.1 (-2.2)	20.8 (+0.2)
Precipitation, cm	17.0 (+5.5)	10.5 (-1.5)	21.3 (+9.8)	15.5 (+7.0)	6.7 (-1.1)	11.3 (+3.6)
2016						
Temperature, °C	14.6 (+0.7)	17.6 (-1.5)	25.1 (+6.4)	25.6 (+0.1)	25.0 (-0.1)	21.9 (+1.1)
Precipitation, cm	14.8 (+3.3)	15.0 (+3.0)	4.7 (-6.8)	22.5 (+14.0)	16.0 (+8.2)	14.6 (+6.9)

†Northern IL, DeKalb in 2014 and 2015, and Yorkville in 2016; Central IL, Champaign; Southern IL, Harrisburg.

2014 RESULTS AND DISCUSSION

Weather Conditions

The 2014 soybean production year experienced near average temperatures with above average precipitation at certain trial locations during the growing season (Table 3). DeKalb and Champaign received precipitation 10.8 cm and 10.1 cm above the 20-year average in June, respectively (Table 3). Champaign also received precipitation 9.9 cm above the 20-year average in July (Table 3). While temperatures remained close to the 20-year average, the month of June in Harrisburg was 5.1 °C warmer (Table 3). Saturated soil conditions may have reduced the amount of N that could be provided through biological N fixation (BNF).

Root Assessments

Although not statistically significant, applications of N fertilizer at preplant slightly decreased nodule number compared to the unfertilized control when averaged across all locations (Table 4). The greatest decrease in nodule number was from application of AN at preplant (Table 4). In contrast, later applications of N fertilizer had less of an effect on the number of nodules, but resulted in a decrease in the pink hue of the nodules (Tables 4 and 5). At the R1 soybean growth stage AMS significantly decreased nodule color (Table 5). Interestingly, significant increases in nodule color resulted from most of the preplant and V3 application times (Table 5), suggesting an increase in nitrogenase activity. While the exact cause of this N-induced increase is unknown, it may have been due to the above average amount of precipitation that the 2014 growing season experienced. In the soil, mineralized ammonium that is converted to nitrate can be lost during waterlogged conditions. Therefore, supplemental N fertilizer applications may have allowed for increased N uptake and nodule activity during conditions of otherwise low N availability.

When examining the individual locations, the effects of N source and application time on nodule number are less apparent. In DeKalb, no N source at any of the four application timings influenced nodule number (Table 6). In Champaign, UAN supplied at the V3 growth stage increased nodule number, while AN supplied at preplant decreased nodule number (Table 6). In Harrisburg, the most apparent decreases in nodule number occurred, where applications of AN, AMS, or UAN inhibited nodule formation at the preplant application timing (Table 6). In regards to nodule color, significant increases in color were found at all three sites. In DeKalb, significant increases in nodule color were present with fertilization of AN during the early season (preplant and V3) application timings (Table 7). In Champaign, significant increases in nodule color occurred from the majority of the N source applications at the preplant and V3 application timings (Table 7). However, decreases in nodule color occurred with the application of AN and AMS at R1 (Table 7). In Harrisburg, there was only one significant decrease in nodule color, which resulted from Urea at the R1 application time (Table 7).

Grain Yield and Yield Components

Averaged across all three locations, the yield of the control (unfertilized) treatments was 4.28 Mg ha^{-1} (73.2 bu ac^{-1}) (Tables 8 and 9). In no instance did any N source supplied at any time decrease yield. All N sources supplied at the preplant growth stage significantly increased yield in 2014 (Tables 8 and 9). Among the various sources, UAN increased yield regardless of the application time and ESN increased yield when supplied up through R1 (Tables 8 and 9). The AN source also significantly increased yield when supplied at V3 (Tables 8 and 9).

When examining the individual locations, variation in yield response to N source and application time was evident. In DeKalb, none of the N sources at any application time decreased yield in 2014 (Tables 10 and 11). All N fertilizer applications made at preplant increased yield by 0.30 to 0.45 Mg ha^{-1} (5.0 to 7.6 bu ac^{-1}), while applications of AN at V3, AMS at V3, AN or ESN at R1, and Urea at R3 also increased yield at DeKalb (Tables 10 and 11). In Champaign, only UAN supplied at preplant significantly increased yield (Tables 10 and 11). In Harrisburg, none of the N sources at any application time decreased yield in 2014 (Tables 10 and 11). The ESN source significantly increased yield when supplied at any of the four application timings (Tables 10 and 11). Significant increases in yield were also obtained by supplying AN at preplant, V3, or R3, AMS at R3, UAN at V3 or R3, and Urea supplied at R1 (Tables 10 and 11).

Based on the yield results from the 2014 growing season, applications made early during the soybean growing season (preplant and V3) significantly increased yield more than applications made later in the growing season (R1 and R3). However, the extent of yield increases varied by individual location, suggesting that soybean responds differently to fertilizer N applications under different soil types and environmental conditions.

Yield components (individual seed weight and seed number) fluctuated by N sources, timing of N applications, and location. Although both seed weight and seed number were enhanced by the addition of fertilizer N, yield increases resulting from N fertilization tended to be more closely associated with increases in seed weight then seed number. For example, significant yield increases that were observed in DeKalb when applications of AMS, UAN, or ESN were made at preplant (Tables 10 and 11) were primarily due to significant increases in seed weight (Table 12). While there was a tendency for N fertilization to increase seed weight to some extent regardless of application time, significant increases in seed weight were apparent in DeKalb when AMS or UAN were supplied at V3, in Champaign when AMS was supplied at R1 or R3, and ESN was supplied at R3, and in Harrisburg when AN was supplied at V3, R1, or R3, when UAN was supplied at R1 or R3, and when AMS or Urea were supplied at R1 (Table 12).

While they were observed, significant increases in seed number occurred less often then significant increases in seed weight (Table 13). Still, in DeKalb in 2014, significant increases in seed number occurred when AN was supplied at preplant, V3, or R1, when ESN was supplied at preplant or V3, and when UAN was supplied at R1 (Table 13). In Champaign, the only significant increase in seed number was when UAN was supplied at preplant (Table 13). In Harrisburg, significant increases in seed number were made when ESN was supplied at preplant and UAN was supplied at V3 (Table 13).

Nitrogen fertilizer applications only seldom affected grain quality (oil and protein concentrations). In DeKalb and Harrisburg in 2014, a few N sources and applications timings increased grain oil concentration slightly, but not enough to be statistically significant (Table 14). In Champaign, significant increases in grain oil concentration resulted from AMS supplied at all four application timings, AN supplied at R3, and UAN supplied at R1 (Table 14). In a similar manner, the locations of DeKalb and Harrisburg only saw minimal non-significant increases in grain protein concentration from various N sources and applications timings. In Champaign, significant increases in grain protein concentration were observed when Urea was supplied at preplant or V3 and when UAN or ESN were supplied at R1 (Table 15).

2014 CONCLUSIONS

The inhibitory effect of fertilizer N applications on soybean nodule development and function was not as severe as previous literature indicated. While nodule number at R4 tended to be reduced by early season (preplant or V3) N applications, the reduction was not statistically significant. Also, in contrast to previous studies, nodule color was actually increased by N applications made at the preplant or V3 application timings. Such increases in nodule color may be indicative of plants with healthy vegetation that may be able to photosynthesize more adequately and in return the soybean may be able to receive more N through the BNF process.

Significant increases in soybean yield occurred most consistently with N fertilization at the preplant application time from the nitrate-containing sources (AN and UAN) and slow-release N source (ESN). However, the variation in yield increases based on site location, N source, and application time indicates that environmental conditions, as well as soil type may play a key role in the response of soybean to fertilizer N applications.

2014 TABLES

Table 4. Soybean nodule number at the R4 growth stage as influenced by N source and plant growth stage at N application averaged across three Illinois locations in 2014. Nodule number is based on a rating scale of 0 to 3. The unfertilized control averaged 2.55.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	nodule number rating			
AN†	1.89	2.65	2.44	2.72
AMS	2.33	2.65	2.61	2.54
UAN	2.28	2.67	2.61	2.57
Urea	2.19	2.59	2.39	2.69
ESN	2.37	2.57	2.67	2.61
LSD (α = 0.10)	NS			

Source of Variation	***P > F***
N Source (S)	0.4170
Application Time (T)	<0.0001
S x T	0.0200

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 5. Soybean nodule color at the R4 growth stage as influenced by N source and plant growth stage at N application averaged across three Illinois locations in 2014. The unfertilized control averaged 60%.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	——nodule color rating %——			
AN†	73*	74*	57	62
AMS	75*	74*	51*	65
UAN	71*	65*	59	61
Urea	76*	62	59	60
ESN	68*	66	65	66
LSD (α = 0.10)		7.3		

Source of Variation	——— ***P > F*** ———
N Source (S)	0.1304
Application Time (T)	<0.0001
S x T	0.0009

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 6. Effect of N source and timing of N application on the soybean nodule number at the R4 growth stage at three locations in Illinois in 2014. For each location, values in parenthesis represent the average nodule number rating of the unfertilized control plots. Values are based on a rating scale of 0 to 3.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	nodule number rating			
	DeKalb (Unfertilized control= 2.88)			
AN†	2.83	2.95	2.78	3.00
AMS	2.78	2.95	3.00	3.00
UAN	2.84	2.94	3.00	2.84
Urea	2.67	3.00	2.83	2.95
ESN	2.72	3.00	2.95	3.00
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 2.36)			
AN	1.78*	2.50	2.39	2.61
AMS	2.34	2.67	2.33	2.22
UAN	2.22	2.95*	2.56	2.39
Urea	1.95	2.72	1.94	2.61
ESN	2.33	2.28	2.39	2.55
LSD (α = 0.10)	0.48			
	Harrisburg (Unfertilized control= 2.42)			
AN	1.06*	2.50	2.17	2.56
AMS	1.89*	2.33	2.50	2.39
UAN	1.78*	2.11	2.28	2.50
Urea	1.95	2.06	2.39	2.50
ESN	2.06	2.44	2.67	2.28
LSD (α = 0.10)	0.50			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 7. Effect of N source and timing of N application on the soybean nodule color at the R4 growth stage at three locations in Illinois in 2014. For each location, values in parenthesis represent the average nodule color rating of the unfertilized control plots. Values are based on a rating scale of 0 to 100%.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	——nodule color rating %——			
	DeKalb (Unfertilized control= 59%)			
AN†	76*	73*	62	65
AMS	67	69	51	61
UAN	72	61	56	51
Urea	66	63	64	62
ESN	65	66	62	65
LSD (α = 0.10)		13		
	Champaign (Unfertilized control= 54%)			
AN	73*	77*	42*	53
AMS	83*	83*	40*	65
UAN	68*	70*	65	66*
Urea	83*	69*	60	51
ESN	73*	60	56	56
LSD (α = 0.10)		11		
	Harrisburg (Unfertilized control= 67%)			
AN	70	71	67	69
AMS	75	67	60	69
UAN	73	64	56	65
Urea	78	54	53*	68
ESN	67	71	77	75
LSD (α = 0.10)		11		

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 8. Grain yield of soybean as influenced by N source and plant growth stage at N application averaged across three Illinois locations in 2014. The unfertilized control averaged 4.28 Mg ha^{-1} (73.2 bu ac^{-1}).

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Mg ha^{-1}			
AN†	4.47*	4.40*	4.37	4.38
AMS	4.42*	4.37	4.36	4.37
UAN	4.48*	4.43*	4.41*	4.40*
Urea	4.44*	4.37	4.35	4.34
ESN	4.53*	4.40*	4.46*	4.35
LSD (α = 0.10)	0.11			
	bu ac^{-1}			
AN	76.4*	75.2*	74.7	74.8
AMS	75.6*	74.7	74.6	74.7
UAN	76.6*	75.7*	75.3*	75.2*
Urea	75.9*	74.7	74.3	74.2
ESN	77.4*	75.2*	76.2*	74.4
LSD (α = 0.10)	1.9			
Source of Variation	***P > F***			
N Source (S)	<0.0001			
Application Time (T)	0.0057			
S x T	0.9970			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 9. Changes in soybean grain yield compared to an unfertilized control as influenced by N fertilizer source and plant growth stage at N fertilization in 2014. Values are averaged over three Illinois locations, three varieties, and six replications. The unfertilized control averaged 4.28 Mg ha^{-1} (73.2 bu ac^{-1}).

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Δ Mg ha^{-1}			
AN†	0.19*	0.12*	0.09	0.10
AMS	0.14*	0.09	0.08	0.09
UAN	0.20*	0.15*	0.13*	0.12*
Urea	0.16*	0.09	0.07	0.06
ESN	0.25*	0.12*	0.18*	0.07
LSD (α = 0.10)	0.11			
	Δ bu ac^{-1}			
AN	3.2*	2.0*	1.5	1.6
AMS	2.4*	1.5	1.4	1.5
UAN	3.4*	2.5*	2.1*	2.0*
Urea	2.7*	1.5	1.1	1.0
ESN	4.2*	2.0*	3.0*	1.2
LSD (α = 0.10)	1.9			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 10. Grain yield of soybean at the individual locations as influenced by the N source and plant growth stage at N fertilization in 2014. For each location, values in parenthesis represent the unfertilized control yields.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Mg ha^{-1}			
	DeKalb (Unfertilized control= 4.09)			
AN†	4.42*	4.35*	4.38*	4.22
AMS	4.54*	4.38*	4.27	4.28
UAN	4.41*	4.27	4.32	4.28
Urea	4.39*	4.34	4.14	4.36*
ESN	4.53*	4.33	4.44*	4.31
LSD (α = 0.10)	0.26			
	Champaign (Unfertilized control= 4.37)			
AN	4.46	4.33	4.23	4.45
AMS	4.36	4.38	4.39	4.34
UAN	4.64*	4.48	4.45	4.41
Urea	4.53	4.37	4.30	4.28
ESN	4.53	4.33	4.42	4.22
LSD (α = 0.10)	0.17			
	Harrisburg (Unfertilized control= 4.36)			
AN	4.52*	4.52*	4.50*	4.47
AMS	4.39	4.37	4.43	4.49*
UAN	4.43	4.55*	4.46	4.51*
Urea	4.40	4.42	4.58*	4.40
ESN	4.54*	4.53*	4.53*	4.51*
LSD (α = 0.10)	0.13			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 11. Changes in soybean grain yield at the individual locations as influenced by the N source and plant growth stage at N fertilization in 2014. For each location, values in parenthesis represent the unfertilized control yields.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	——— Δ Mg ha^{-1} ———			
	DeKalb (Unfertilized control= 4.09)			
AN†	0.33*	0.26*	0.29*	0.13
AMS	0.45*	0.29*	0.18	0.19
UAN	0.32*	0.18	0.23	0.19
Urea	0.30*	0.25	0.05	0.27*
ESN	0.44*	0.24	0.35*	0.22
LSD (α = 0.10)	0.26			
	Champaign (Unfertilized control= 4.37)			
AN	0.09	-0.04	-0.14	0.08
AMS	-0.01	0.00	0.01	-0.04
UAN	0.27*	0.11	0.08	0.04
Urea	0.16	0.00	-0.07	-0.09
ESN	0.16	-0.04	0.04	-0.15
LSD (α = 0.10)	0.17			
	Harrisburg (Unfertilized control= 4.36)			
AN	0.16*	0.16*	0.14*	0.11
AMS	0.03	0.00	0.06	0.13*
UAN	0.07	0.19*	0.09	0.15*
Urea	0.04	0.06	0.22*	0.04
ESN	0.18*	0.17*	0.17*	0.15*
LSD (α = 0.10)	0.13			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 12. Effect of N source and timing of N application on soybean seed weight at three locations in Illinois in 2014. For each location, values in parenthesis represent the individual seed weight produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	mg seed^{-1}			
	DeKalb (Unfertilized control= 151.9 mg seed^{-1})			
AN†	157.2	157.6	148.6	156.0
AMS	160.7*	158.5*	156.6	156.2
UAN	160.7*	158.5*	154.0	156.9
Urea	156.2	157.7	149.9	156.9
ESN	159.1*	156.2	157.4	156.5
LSD (α = 0.10)	6.0			
	Champaign (Unfertilized control= 155.1 mg seed^{-1})			
AN	158.7	157.7	157.1	158.4
AMS	156.6	154.2	161.0*	159.5*
UAN	153.9	154.4	157.6	156.7
Urea	158.8	158.7	156.7	156.5
ESN	157.8	157.3	156.8	160.5*
LSD (α = 0.10)	4.0			
	Harrisburg (Unfertilized control= 137.7 mg seed^{-1})			
AN	139.2	146.6*	143.2*	143.4*
AMS	139.9	138.7	141.4*	138.3
UAN	140.8	138.5	142.5*	143.0*
Urea	140.4	139.4	143.7*	140.9
ESN	139.4	140.1	140.1	140.8
LSD (α = 0.10)	3.5			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 13. Effect of N source and timing of N application on soybean seed number at three locations in Illinois in 2014. For each location, values in parenthesis represent the number of seeds produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	seed m^{-2}			
	DeKalb (Unfertilized control= 2562 seed m^{-2})			
AN†	2839*	2834*	2971*	2786
AMS	2625	2559	2557	2577
UAN	2746	2698	2812*	2735
Urea	2715	2609	2661	2704
ESN	2857*	2781	2827*	2760
LSD (α = 0.10)	238			
	Champaign (Unfertilized control= 2824 seed m^{-2})			
AN	2817	2752	2701	2814
AMS	2794	2842	2727	2720
UAN	3181*	2903	2897	2830
Urea	2859	2756	2749	2735
ESN	2870	2764	2819	2631
LSD (α = 0.10)	158			
	Harrisburg (Unfertilized control= 3167 seed m^{-2})			
AN	3252	3085	3147	3116
AMS	3145	3150	3131	3249
UAN	3149	3285*	3131	3159
Urea	3140	3171	3190	3126
ESN	3258*	3239	3231	3203
LSD (α = 0.10)	89			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 14. Effect of N source and timing of N application on the concentration of soybean grain oil at three locations in Illinois in 2014. For each location, values in parenthesis represent the concentration of grain oil produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	oil %			
	DeKalb (Unfertilized control= 17.4%)			
AN†	17.4	17.1	17.5	17.4
AMS	17.2	17.2	17.5	17.5
UAN	17.4	17.4	17.4	17.4
Urea	17.3	17.4	17.5	17.5
ESN	17.6	17.4	17.4	17.3
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 19.3%)			
AN	19.2	19.6	19.6	19.7*
AMS	19.9*	19.8*	19.9*	19.7*
UAN	19.3	19.3	19.7*	19.5
Urea	19.6	19.5	19.3	19.4
ESN	19.5	19.2	19.6	19.4
LSD (α = 0.10)	0.4			
	Harrisburg (Unfertilized control= 19.8%)			
AN	19.8	19.8	19.6	19.7
AMS	20.0	19.8	19.7	20.0
UAN	19.6	19.6	19.9	19.8
Urea	19.4	19.3	19.7	19.5
ESN	19.9	19.9	19.4	19.6
LSD (α = 0.10)	NS			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

Table 15. Effect of N source and timing of N application on the concentration of soybean grain protein at three locations in Illinois in 2014. For each location, values in parenthesis represent the concentration of grain protein produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	protein %			
	DeKalb (Unfertilized control= 36.0%)			
AN†	36.1	36.2	35.8	35.9
AMS	36.1	36.3	35.8	35.7
UAN	36.0	35.9	35.8	35.8
Urea	35.9	36.0	35.7	35.7
ESN	36.1	36.0	35.8	36.3
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 28.3%)			
AN	26.2	30.2	30.1	30.6
AMS	33.3	33.2	33.4	34.1
UAN	31.0	30.8	33.9*	30.9
Urea	33.8*	34.0*	27.6	34.1
ESN	34.1	30.1	33.9*	34.3
LSD (α = 0.10)	5.2			
	Harrisburg (Unfertilized control= 30.0%)			
AN	30.0	29.9	30.2	30.2
AMS	32.2	29.8	27.7	32.1
UAN	32.2	30.0	32.3	29.9
Urea	29.8	25.7	30.1	27.7
ESN	32.2	32.1	27.9	27.9
LSD (α = 0.10)	NS			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, and ESN is controlled release polymer-coated urea.

2015 RESULTS AND DISCUSSION

Weather Conditions

The 2015 soybean production year experienced near average temperatures, but above average spring precipitation at all sites (Table 3). The entire state of Illinois experienced a record amount of precipitation in June (records dating back to 1886). DeKalb received 20.2 cm compared to the 20-year average of 9.9 cm, Champaign received 23.3 cm compared to the 20-year average of 10.8 cm, and Harrisburg received 21.3 cm compared to the 20-year average of 11.5 cm (Table 3). However, following the above average precipitation in June, the DeKalb and Champaign sites experienced below-average precipitation for July and August, while Harrisburg experienced below-average precipitation in August only (Table 3). Increased precipitation in June could have limited to ability of the nodules to supply N through BNF.

Grain Yield and Yield Components

Averaged across all three locations, the yield of the control (unfertilized) treatment was 4.20 Mg ha^{-1} (71.7 bu ac^{-1}) in 2015 (Tables 16 and 17). When averaged over the three locations, all fertilizer N sources supplied at the preplant application time significantly increased yield, as did all fertilizer N sources supplied at the R3 soybean growth stage (Tables 16 and 17). Other significant increases in yield occurred when AN, UAN, or Urea + Limus were supplied at V3 and when AN, UAN, AN+KN+AMS, or ESN were supplied at R1 (Tables 16 and 17). The AN supplied at preplant and R3 resulted in the greatest yield increases of 0.30 Mg ha^{-1} (5.3 bu ac^{-1}) and 0.32 Mg ha^{-1} (5.5 bu ac^{-1}), respectively (Tables 16 and 17).

When examining the individual locations, variation in the N source and the application time that gave the greatest yield increase was evident. At DeKalb, the majority of significant yield increases occurred at the R1 application time, specifically with the application of AN, UAN, Urea + Limus, or AN+KN+AMS (Tables 18 and 19). The application of AN at DeKalb in

2015 at preplant increased yield notably by 0.62 Mg ha^{-1} (10.6 bu ac^{-1}) (Tables 18 and 19). In Champaign, applications at the V3 growth stage of AN and application at the R3 growth stage of AN, AMS, Urea, Urea + Limus, or AN+KN+AMS significantly increased yield (Tables 18 and 19). In Harrisburg, significant yield increases occurred from the preplant applications, during which UAN, Urea + Limus, AN+KN+AMS, or ESN all significantly increased yield (Tables 18 and 19). Significant yield increases also resulted from the application of UAN at V3 and the application of AN or Urea + Limus at R3 (Tables 18 and 19).

Based on the yield results from the 2015 growing season, applications of N during the preplant, R1 or R3 soybean growth stages produced the greatest yield responses. While almost all N sources significantly increased yield, the nitrate-containing sources (AN and UAN) and ESN produced the greatest yield increases when averaged over all locations. As noted earlier, all locations received an amount of precipitation that was almost double that of the 20-year average (Table 3). Saturated soil conditions during the month of June likely amplified the amount of residual N lost through leaching and denitrification.

Although both seed weight and seed number were enhanced by the addition of fertilizer N, yield increases resulting from N fertilization tended to be more closely associated with increases in seed weight than seed number. For example, the yield increases observed from N fertilization in DeKalb (Tables 18 and 19) were primarily due to increases in seed weight (Table 20), and were mainly associated with the vegetative (preplant and V3) and the early reproductive (R1) applications. Other large yield increases observed from N fertilizer applications in Champaign at R3 and Harrisburg at preplant (Tables 18 and 19) were also primarily the result of heavier individual seed weights (Tables 20). Seed number was only increased significantly by a few N fertilizer sources at select sites. However, seed number overall was markedly higher at the Harrisburg location, which also had the highest overall yields (Table 21).

In general, the N applications did not affect grain quality (oil and protein concentrations). There were sporadic increases in grain oil concentrations at each location when N was supplied at R1 or R3 (Table 22). Also sporadic, increases in grain protein concentration tended to be more associated with early N applications, especially at Harrisburg where ESN and Urea + Limus at preplant and Urea and Urea + Limus at V3 increased grain protein concentration (Table 23).

2015 CONCLUSIONS

During the 2015 growing season, soybean yields were increased the most commonly from preplant, R1, or R3 applications with the use of nitrate-containing sources (AN, UAN, or AN+KN+AMS) and slow-release N sources (Urea + Limus or ESN). Following a period of rainfall nearly twice the amount of the 20-year average, it is likely that a large amount of residual N was lost through leaching and denitrification, and that BNF activity was slowed due to the waterlogged soil environment. Therefore, supplemental N applications may have the ability to create substantial yield increases during growing seasons when an abundant amount of precipitation occurs.

2015 TABLES

Table 16. Grain yield of soybean as influenced by N source and plant growth stage at N application averaged across three Illinois locations in 2015. The unfertilized control averaged 4.20 Mg ha^{-1} (71.7 bu ac^{-1}).

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Mg ha^{-1}			
AN†	4.50*	4.43*	4.46*	4.52*
AMS	4.43*	4.28	4.35	4.42*
UAN	4.47*	4.42*	4.37*	4.36*
Urea	4.40*	4.35	4.33	4.37*
Urea + Limus	4.36*	4.38*	4.35	4.43*
AN+KN+AMS	4.42*	4.27	4.41*	4.41*
ESN	4.46*	4.34	4.40*	4.36*
LSD (α = 0.10)	0.16			
	bu ac^{-1}			
AN†	77.0*	75.7*	76.2*	77.2*
AMS	75.6*	73.1	74.4	75.6*
UAN	76.4*	75.6*	74.7*	74.6*
Urea	75.3*	74.4	74.1	74.6*
Urea + Limus	74.5*	74.8*	74.4	75.7*
AN+KN+AMS	75.6*	72.9	75.4*	75.4*
ESN	76.2*	74.2	75.2*	74.6*
LSD (α = 0.10)	2.8			

Source of Variation	***P > F***
N Source (S)	<0.0001
Application Time (T)	0.0780
S x T	0.9953

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 17. Changes in soybean grain yield compared to an unfertilized control as influenced by N fertilizer source and plant growth stage at N fertilization in 2015. Values are averaged over three Illinois locations, three varieties, and six replications. The unfertilized control averaged 4.20 Mg ha^{-1} (71.7 bu ac^{-1}).

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Δ Mg ha^{-1}			
AN†	0.30*	0.23*	0.26*	0.32*
AMS	0.23*	0.08	0.15	0.22*
UAN	0.27*	0.22*	0.17*	0.16*
Urea	0.20*	0.15	0.13	0.17*
Urea + Limus	0.16*	0.18*	0.15	0.23*
AN+KN+AMS	0.22*	0.07	0.21*	0.21*
ESN	0.26*	0.14	0.20*	0.16*
LSD (α = 0.10)	0.16			
	Δ bu ac^{-1}			
AN†	5.3*	4.0*	4.5*	5.5*
AMS	3.9*	1.4	2.7	3.9*
UAN	4.7*	3.9*	3.0*	2.9*
Urea	3.6*	2.7	2.4	2.9*
Urea + Limus	2.8*	3.1*	2.7	4.0*
AN+KN+AMS	3.9*	1.2	3.7*	3.7*
ESN	4.5*	2.5	3.5*	2.9*
LSD (α = 0.10)	2.8			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 18. Grain yield of soybean at the individual locations as influenced by the N source and plant growth stage at N fertilization in 2015. For each location, values in parenthesis represent the unfertilized control yields.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Mg ha^{-1}			
	DeKalb (Unfertilized control= 3.70 Mg ha^{-1})			
AN†	4.32*	4.09*	4.13*	3.96
AMS	4.03*	3.84	3.79	3.85
UAN	3.88	3.96	4.01*	3.80
Urea	3.91	3.86	3.79	3.83
Urea + Limus	3.84	3.80	4.12*	3.73
AN+KN+AMS	3.91	3.90	4.04*	3.72
ESN	3.89	3.98	3.86	3.85
LSD (α = 0.10)	0.31			
	Champaign (Unfertilized control= 4.29 Mg ha^{-1})			
AN	4.53*	4.52*	4.54*	4.69*
AMS	4.54*	4.40	4.55*	4.61*
UAN	4.50	4.42	4.40	4.48
Urea	4.51	4.40	4.51	4.53*
Urea + Limus	4.31	4.47	4.45	4.54*
AN+KN+AMS	4.49	4.45	4.46	4.63*
ESN	4.47	4.43	4.48	4.41
LSD (α = 0.10)	0.23			
	Harrisburg (Unfertilized control= 4.60 Mg ha^{-1})			
AN	4.66	4.67	4.70	4.90*
AMS	4.72	4.59	4.71	4.81
UAN	5.06*	4.89*	4.70	4.81
Urea	4.80	4.80	4.70	4.74
Urea + Limus	4.93*	4.86	4.48	5.02*
AN+KN+AMS	4.88*	4.45	4.73	4.85
ESN	5.00*	4.61	4.86	4.83
LSD (α = 0.10)	0.27			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 19. Changes in soybean grain yield at the individual locations as influenced by the N source and plant growth stage at N fertilization in 2015. For each location, values in parenthesis represent the unfertilized control yields. Positive values are indicative of yield increases and negative values of yield decreases.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Δ Mg ha^{-1}			
	DeKalb (Unfertilized control= 3.70 Mg ha^{-1})			
AN†	0.62*	0.39*	0.43*	0.26
AMS	0.33*	0.14	0.09	0.15
UAN	0.18	0.26	0.31*	0.10
Urea	0.21	0.16	0.09	0.13
Urea + Limus	0.14	0.10	0.42*	0.03
AN+KN+AMS	0.21	0.20	0.34*	0.02
ESN	0.19	0.28	0.16	0.15
LSD (α = 0.10)	0.31			
	Champaign (Unfertilized control= 4.29 Mg ha^{-1})			
AN	0.24*	0.23*	0.25*	0.40*
AMS	0.25*	0.11	0.26*	0.32*
UAN	0.21	0.13	0.11	0.19
Urea	0.22	0.11	0.22	0.24*
Urea + Limus	0.02	0.18	0.16	0.25*
AN+KN+AMS	0.20	0.16	0.17	0.34*
ESN	0.18	0.14	0.19	0.12
LSD (α = 0.10)	0.23			
	Harrisburg (Unfertilized control= 4.60 Mg ha^{-1})			
AN	0.06	0.07	0.10	0.30*
AMS	0.12	-0.01	0.11	0.21
UAN	0.46*	0.29*	0.10	0.21
Urea	0.20	0.20	0.10	0.14
Urea + Limus	0.33*	0.26	-0.12	0.42*
AN+KN+AMS	0.28*	-0.15	0.13	0.25
ESN	0.40*	0.01	0.26	0.23
LSD (α = 0.10)	0.27			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 20. Effect of N source and timing of N application on soybean seed weight at three locations in Illinois in 2015. For each location, values in parenthesis represent the individual seed weight produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	mg seed^{-1}			
	DeKalb (Unfertilized control= 146.5 mg seed^{-1})			
AN†	155.5*	153.0*	155.7*	145.7
AMS	156.3*	148.8	151.5	145.0
UAN	152.5*	153.4*	154.3*	148.9
Urea	150.9	152.4*	151.0	149.9
Urea + Limus	153.3*	154.6*	156.2*	149.1
AN+KN+AMS	151.1	152.4*	154.1*	147.3
ESN	149.8	145.7	146.5	148.4
LSD (α = 0.10)	5.6			
	Champaign (Unfertilized control= 172.7 mg seed^{-1})			
AN	177.6*	176.8	178.3*	175.3
AMS	177.1*	176.8	178.0*	178.2*
UAN	172.3	172.7	175.3	175.2
Urea	175.0	175.5	171.2	173.1
Urea + Limus	174.9	175.0	173.2	175.1
AN+KN+AMS	177.7*	175.7	178.8*	173.5
ESN	174.9	173.1	172.7	170.6
LSD (α = 0.10)	4.4			
	Harrisburg (Unfertilized control= 140.3 mg seed^{-1})			
AN	141.3	142.5	142.7	144.7*
AMS	142.4	138.0	140.5	144.6*
UAN	146.3*	144.2*	140.8	142.9
Urea	143.7	144.7*	139.8	143.4
Urea + Limus	145.3*	144.7*	139.3	147.6*
AN+KN+AMS	143.7	140.7	141.9	143.1
ESN	147.6*	141.9	143.1	145.6
LSD (α = 0.10)	3.9			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 21. Effect of N source and timing of N application on soybean seed number at three locations in Illinois in 2015. For each location, values in parenthesis represent the number of seeds produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	seed m^{-2}			
	DeKalb (Unfertilized control= 2528 seed m^{-2})			
AN†	2782*	2681	2655	2721*
AMS	2576	2575	2500	2578
UAN	2552	2584	2600	2554
Urea	2594	2535	2513	2557
Urea + Limus	2505	2462	2642	2507
AN+KN+AMS	2590	2561	2627	2534
ESN	2605	2737*	2636	2592
LSD (α = 0.10)	184			
	Champaign (Unfertilized control= 2487 seed m^{-2})			
AN	2559	2589	2575	2639*
AMS	2568	2477	2579	2590
UAN	2614	2530	2554	2563
Urea	2583	2546	2575	2652*
Urea + Limus	2464	2554	2545	2626*
AN+KN+AMS	2529	2566	2495	2595
ESN	2563	2663*	2594	2558
LSD (α = 0.10)	136			
	Harrisburg (Unfertilized control= 3253 seed m^{-2})			
AN	3299	3278	3295	3387
AMS	3317	3327	3352	3329
UAN	3465*	3394	3341	3367
Urea	3343	3322	3368	3305
Urea + Limus	3399	3358	3224	3407
AN+KN+AMS	3400	3167	3340	3391
ESN	3394	3252	3396	3320
LSD (α = 0.10)	158			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 22. Effect of N source and timing of N application on the concentration of soybean grain oil at three locations in Illinois in 2015. For each location, values in parenthesis represent the concentration of grain oil produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	oil %			
	DeKalb (Unfertilized control= 18.2%)			
AN†	18.1	18.1	18.2	18.2
AMS	18.2	18.4*	18.5*	18.2
UAN	18.2	18.2	18.2	18.3
Urea	18.2	18.2	18.3	18.1
Urea + Limus	18.2	18.1	18.3	18.3
AN+KN+AMS	18.2	18.3	18.2	18.3
ESN	18.2	18.2	18.3	18.1
LSD (α = 0.10)	0.2			
	Champaign (Unfertilized control= 19.2%)			
AN	19.0	19.0	19.3	19.3
AMS	19.1	19.2	19.2	19.1
UAN	19.3	19.1	19.3	19.4*
Urea	19.2	19.2	19.3	19.3
Urea + Limus	19.3	19.3	19.4*	19.5*
AN+KN+AMS	19.0	19.2	19.4*	19.3
ESN	19.2	19.2	19.3	19.1
LSD (α = 0.10)	0.2			
	Harrisburg (Unfertilized control= 20.0%)			
AN	20.0	19.9	20.0	20.2*
AMS	20.0	20.1	20.3*	20.1
UAN	19.8	19.9	19.9	20.3*
Urea	19.9	19.8	20.0	20.2*
Urea + Limus	19.9	19.8	20.1	20.2*
AN+KN+AMS	19.9	20.1	20.2*	20.3*
ESN	19.9	19.9	20.1	20.0
LSD (α = 0.10)	0.2			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 23. Effect of N source and timing of N application on the concentration of soybean grain protein at three locations in Illinois in 2015. For each location, values in parenthesis represent the concentration of grain protein produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	protein %			
	DeKalb (Unfertilized control= 34.1%)			
AN†	34.5	34.3	34.3	34.2
AMS	34.3	33.7	33.7	34.1
UAN	34.3	34.3	34.1	34.2
Urea	34.1	33.9	34.0	34.3
Urea + Limus	34.2	34.4	34.4	33.9
AN+KN+AMS	34.0	34.1	34.2	34.1
ESN	34.2	34.0	34.0	34.3
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 34.5%)			
AN	35.0	34.8	34.5	34.7
AMS	34.7	34.5	34.6	35.0
UAN	34.3	34.6	34.4	34.2
Urea	34.6	34.7	34.5	34.2
Urea + Limus	34.6	34.5	34.4	34.2
AN+KN+AMS	34.7	34.4	34.3	34.6
ESN	34.6	34.4	34.4	34.5
LSD (α = 0.10)	NS			
	Harrisburg (Unfertilized control= 34.4%)			
AN	34.4	34.6	34.3	34.4
AMS	34.4	34.3	34.0	34.3
UAN	34.6	34.6	34.5	34.0
Urea	34.6	34.8*	34.3	34.3
Urea + Limus	34.7*	34.7*	34.3	34.4
AN+KN+AMS	34.6	34.3	34.2	34.2
ESN	34.8*	34.5	34.4	34.5
LSD (α = 0.10)	0.3			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

2016 RESULTS AND DISCUSSION

Weather Conditions

The 2016 soybean production year experienced near average temperatures, but above average precipitation in May at certain locations (Table 3). Modest above average precipitation also occurred in July in Yorkville, in June and September in Champaign, and in July, August, and September in Harrisburg, too (Table 3). Yorkville was distinctly cooler than Champaign and Harrisburg (Table 3). The overall weather conditions of 2016 growing season were optimal for soybean production, with little heat or moisture stress.

Grain Yield and Yield Components

Averaged across all locations, the yield of the control (unfertilized) treatments was 4.35 Mg ha^{-1} (74.4 bu ac^{-1}) (Tables 24 and 25). Furthermore, when averaged over the three locations, the N fertilizer sources AN, UAN, Urea, AN+KN+AMS, or ESN supplied at preplant significantly increased yield (Tables 24 and 25). In no instance did any N source supplied at any time decrease yield when averaged across all locations. Among the various N sources, preplant fertilization with AN resulted in the greatest yield increase of 0.18 Mg ha^{-1} (3.1 bu ac^{-1}), followed by UAN and AN+KN+AMS where both N sources increased yield by 0.17 Mg ha^{-1} (2.9 bu ac^{-1}), followed by ESN which increased yield by 0.16 Mg ha^{-1} (2.6 bu ac^{-1}) (Tables 24 and 25).

Distinction in yield response to N source and the fertilization time was apparent in 2016. In Yorkville, fertilization with AN or Urea + Limus tended to decrease yield at all four application times (Tables 26 and 27). Because the pre-planting soil test results for Yorkville showed that the amount of residual N in the soil was high (Table 1), the need for supplemental N at this location may be limited during years when mineralization of soil N is high and loss of residual N from the soil is low. In Champaign, all N sources significantly increased yield when supplied at the preplant application time (Tables 26 and 27). Fertilization with AN increased yield when provided at the first three fertilization times at Champaign (Tables 26 and 27). Additionally, at Champaign fertilization with AN+KN+AMS or ESN at the preplant orV3 growth stage increased yield, while AMS produced a yield increase when supplied at the R3 growth stage (Tables 26 and 27). At Harrisburg, preplant applications of AN, UAN, or ESN resulted in yield increases of 0.27, 0.17, and 0.18 Mg ha^{-1} (4.7, 2.9, and 3.1 bu ac^{-1}), respectively (Tables 26 and 27). The applications of Urea + Limus at the R1 growth stage and Urea at the R3 growth stage also significantly increased yield (Tables 26 and 27). Interestingly, the application of ESN at Harrisburg at the R1 growth stage significantly decreased yield (Tables 26 and 27).

Based on the yield results from the 2016 growing season, the early season application of N (specifically at preplant) produced the greatest yield response. Significant yield increases at the preplant application time may account for the fact that soybean nodules are not formed until the V2 soybean growth stage, meaning supplemental N fertilizer at the preplant application time may prevent the soybean from experiencing any N deficiency at the start of the growing season.

Yield components (individual seed weight and seed number) were influenced by the N sources, the timing of N application, and the trial location. In Yorkville, most N applications and timings increased seed weight non-significantly (Table 28). In Champaign, significant increases in seed weight occurred most often from preplant applications, especially AN, UAN, Urea, or Urea + Limus (Table 28). Other significant increases in seed weight were noted from the application of AN, Urea + Limus, or AN+KN+AMS at V3 and Urea at R3 (Table 28). In Harrisburg, increases in seed weight occurred from the application of AN at preplant, AMS at V3 or R1, and Urea at R1 (Table 28). Seed number was enhanced less often than seed weight from N fertilization. In Yorkville, some N treatments increased seed number, although all were non-significant (Table 29). In Champaign, significant increases in seed number occurred when AMS was supplied at preplant, V3, or R3 and when AN+KN+AMS was supplied at preplant (Table 29). In Harrisburg, significant increases in seed number were only generated twice, when AN was supplied at preplant and when Urea + Limus was supplied at R1 (Table 29).

In Yorkville and Champaign, no significant increases in grain oil concentration occurred from any of the N sources at any application time (Table 30). In Harrisburg, surprisingly all R1 applications significantly increased grain oil concentration (Table 30). Additional significant increases in grain oil concentrations were observed from N applications at V3 or R3 (Table 30). The concentration of grain protein was not significantly increased by any N applications at any of the three sites in 2016 (Table 31).

2016 CONCLUSIONS

The 2016 production year generated high yields in many locations across the Midwest. Even with satisfactory weather conditions, soybean responded to N fertilization made at the preplant application time. The N sources: AN, UAN, Urea, AN+KN+AMS, and ESN all increased yield. In Yorkville, failure of N fertilization to increase yield is likely due to the highly productive soil found in this environment, which was validated with pre-planting soil test results that contained high amounts of NH_4^+ and NO_3^-, as well as a high percentage of soil organic matter (Table 1). At the early stages of soybean growth, supplemental N applications may eliminate the possibility of early N deficiency.

2016 TABLES

Table 24. Grain yield of soybean as influenced by N source and plant growth stage at N application averaged across three Illinois locations in 2016. The unfertilized control averaged 4.35 Mg ha^{-1} (74.4 bu ac^{-1}).

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Mg ha^{-1}			
AN†	4.53*	4.37	4.37	4.37
AMS	4.42	4.29	4.34	4.39
UAN	4.52*	4.35	4.36	4.39
Urea	4.47*	4.29	4.37	4.46
Urea + Limus	4.44	4.40	4.42	4.34
AN+KN+AMS	4.52*	4.41	4.35	4.36
ESN	4.51*	4.46	4.29	4.38
LSD (α = 0.10)	0.12			
	bu ac^{-1}			
AN†	77.5*	74.7	74.7	74.7
AMS	75.6	73.4	74.2	75.1
UAN	77.2*	74.4	74.5	75.0
Urea	76.4*	73.3	74.8	76.2
Urea + Limus	75.8	75.2	75.5	74.2
AN+KN+AMS	77.3*	75.3	74.3	74.6
ESN	77.0*	76.2	73.4	74.9
LSD (α = 0.10)	2.0			
Source of Variation	***P* > *F***			
N Source (S)	0.5223			
Application Time (T)	<0.0001			
S x T	0.3562			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 25. Changes in soybean grain yield compared to an unfertilized control as influenced by N fertilizer source and plant growth stage at N fertilization in 2016. Values are averaged over three Illinois locations, three varieties, and six replications. The unfertilized control averaged 4.35 Mg ha^{-1} (74.4 bu ac^{-1}).

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Δ Mg ha^{-1}			
AN†	0.18*	0.02	0.02	0.02
AMS	0.07	-0.06	-0.01	0.04
UAN	0.17*	0.00	0.01	0.04
Urea	0.12*	-0.06	0.02	0.11
Urea + Limus	0.09	0.05	0.07	-0.01
AN+KN+AMS	0.17*	0.06	0.00	0.01
ESN	0.16*	0.11	-0.06	0.03
LSD (α = 0.10)		0.12		
	Δ bu ac^{-1}			
AN†	3.1*	0.3	0.3	0.3
AMS	1.2	-1.0	-0.2	0.6
UAN	2.8*	-0.1	0.1	0.6
Urea	2.0*	-1.1	0.3	1.8
Urea + Limus	1.4	0.8	1.1	-0.2
AN+KN+AMS	2.9*	0.9	-0.1	0.2
ESN	2.6*	1.8	-1.1	0.5
LSD (α = 0.10)		2.0		

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 26. Grain yield of soybean at the individual locations as influenced by the N source and plant growth stage at N fertilization in 2016. For each location, values in parenthesis represent the unfertilized control yields.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Mg ha^{-1}			
	Yorkville (Unfertilized control= 5.22 Mg ha^{-1})			
AN†	5.13	5.04	5.10	5.14
AMS	5.08	5.04	5.27	5.19
UAN	5.32	5.22	5.14	5.12
Urea	5.21	5.06	5.31	5.29
Urea + Limus	5.13	5.13	5.19	5.10
AN+KN+AMS	5.27	5.20	5.25	5.31
ESN	5.29	5.29	5.18	5.21
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 4.48 Mg ha^{-1})			
AN	4.81*	4.68*	4.69*	4.60
AMS	4.89*	4.66	4.62	4.77*
UAN	4.71*	4.55	4.50	4.61
Urea	4.75*	4.48	4.51	4.55
Urea + Limus	4.79*	4.61	4.43	4.61
AN+KN+AMS	4.80*	4.70*	4.54	4.51
ESN	4.69*	4.68*	4.51	4.62
LSD (α = 0.10)	0.19			
	Harrisburg (Unfertilized control= 3.35 Mg ha^{-1})			
AN	3.62*	3.39	3.33	3.37
AMS	3.30	3.17	3.14	3.22
UAN	3.52*	3.28	3.43	3.44
Urea	3.46	3.32	3.30	3.54*
Urea + Limus	3.37	3.45	3.59*	3.31
AN+KN+AMS	3.51	3.32	3.25	3.27
ESN	3.53*	3.43	3.18	3.33
LSD (α = 0.10)	0.17			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 27. Changes in soybean grain yield at the individual locations as influenced by the N source and plant growth stage at N fertilization in 2016. For each location, values in parenthesis represent the unfertilized control yields. Positive values are indicative of yield increases and negative values of yield decreases.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Δ Mg ha^{-1}			
	Yorkville (Unfertilized control= 5.22 Mg ha^{-1})			
AN†	-0.09	-0.18	-0.12	-0.08
AMS	-0.14	-0.18	0.05	-0.03
UAN	0.10	0.00	-0.08	-0.10
Urea	-0.01	-0.16	0.09	0.07
Urea + Limus	-0.09	-0.09	-0.03	-0.12
AN+KN+AMS	0.05	-0.02	0.03	0.09
ESN	0.07	0.07	-0.04	-0.01
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 4.48 Mg ha^{-1})			
AN	0.33*	0.20*	0.21*	0.12
AMS	0.41*	0.18	0.14	0.29*
UAN	0.23*	0.07	0.02	0.13
Urea	0.27*	0.00	0.03	0.07
Urea + Limus	0.31*	0.13	-0.05	0.13
AN+KN+AMS	0.32*	0.22*	0.06	0.03
ESN	0.21*	0.20*	0.03	0.14
LSD (α = 0.10)	0.19			
	Harrisburg (Unfertilized control= 3.35 Mg ha^{-1})			
AN	0.27*	0.04	-0.02	0.02
AMS	-0.05	-0.18	-0.21	-0.13
UAN	0.17*	-0.07	0.08	0.09
Urea	0.11	-0.03	-0.05	0.19*
Urea + Limus	0.02	0.10	0.24*	-0.04
AN+KN+AMS	0.16	-0.03	-0.10	-0.08
ESN	0.18*	0.08	-0.17*	-0.02
LSD (α = 0.10)	0.17			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 28. Effect of N source and timing of N application on soybean seed weight at three locations in Illinois in 2016. For each location, values in parenthesis represent the individual seed weight produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	mg seed^{-1}			
	Yorkville (Unfertilized control= 158.9 mg seed^{-1})			
AN†	157.3	158.1	157.6	159.9
AMS	158.6	159.8	158.0	160.4
UAN	159.0	160.2	157.1	156.2
Urea	162.9	161.5	157.8	160.6
Urea + Limus	160.5	156.1	157.4	158.7
AN+KN+AMS	161.3	159.8	159.4	157.2
ESN	161.4	159.2	157.9	158.7
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 159.1 mg seed^{-1})			
AN	165.9*	164.6*	161.0	158.4
AMS	162.1	157.6	161.9	159.2
UAN	164.1*	160.8	161.9	162.7
Urea	165.5*	163.2	160.7	163.6*
Urea + Limus	164.2*	166.2*	161.4	162.6
AN+KN+AMS	161.3	163.3*	159.3	162.6
ESN	162.5	161.8	161.9	157.4
LSD (α = 0.10)	4.2			
	Harrisburg (Unfertilized control= 118.5 mg seed^{-1})			
AN	122.2*	119.7	117.7	117.6
AMS	118.7	113.1*	114.5*	119.1
UAN	120.0	120.2	116.7	117.2
Urea	120.6	118.0	114.5*	120.9
Urea + Limus	120.4	118.8	118.2	118.8
AN+KN+AMS	120.0	115.9	115.5	118.9
ESN	117.6	118.2	118.1	115.3
LSD (α = 0.10)	3.4			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 29. Effect of N source and timing of N application on soybean seed number at three locations in Illinois in 2016. For each location, values in parenthesis represent the number of seeds produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	seed m^{-2}			
	Yorkville (Unfertilized control= 3290 seed m^{-2})			
AN†	3265	3197	3180	3222
AMS	3205	3121	3338	3246
UAN	3344	3259	3277	3280
Urea	3205	3141	3370	3295
Urea + Limus	3194	3289	3305	3223
AN+KN+AMS	3272	3257	3296	3383
ESN	3284	3325	3288	3288
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 2819 seed m^{-2})			
AN	2901	2846	2914	2928
AMS	3018*	2958*	2857	3001*
UAN	2882	2835	2788	2838
Urea	2873	2752	2808	2780
Urea + Limus	2923	2778	2762	2839
AN+KN+AMS	2999*	2874	2852	2780
ESN	2892	2898	2791	2939
LSD (α = 0.10)	130			
	Harrisburg (Unfertilized control= 2866 seed m^{-2})			
AN	3026*	2824	2839	2889
AMS	2822	2997	2708	2665
UAN	2920	2789	2925	2861
Urea	2858	2918	2853	2942
Urea + Limus	2806	2896	3042*	2799
AN+KN+AMS	2918	2876	2759	2780
ESN	3012	2870	2785	2887
LSD (α = 0.10)	151			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$
†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 30. Effect of N source and timing of N application on the concentration of soybean grain oil at three locations in Illinois in 2016. For each location, values in parenthesis represent the concentration of grain oil produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	oil %			
	Yorkville (Unfertilized control= 18.5%)			
AN†	18.4	18.7	18.7	18.6
AMS	18.5	18.6	18.6	18.7
UAN	18.6	18.6	18.7	18.7
Urea	18.5	18.5	18.5	18.7
Urea + Limus	18.7	18.6	18.6	18.6
AN+KN+AMS	18.5	18.7	18.7	18.7
ESN	18.5	18.7	18.5	18.6
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 18.8%)			
AN	18.7	18.8	18.9	18.9
AMS	18.7	18.8	18.8	18.9
UAN	18.8	18.8	18.8	18.9
Urea	18.7	18.7	18.7	18.8
Urea + Limus	18.8	18.6	18.8	18.9
AN+KN+AMS	18.8	18.7	18.8	18.8
ESN	18.8	18.7	18.8	18.9
LSD (α = 0.10)	NS			
	Harrisburg (Unfertilized control= 20.0%)			
AN	20.1	20.3*	20.4*	20.4*
AMS	20.0	20.3*	20.2*	20.3*
UAN	20.0	20.2*	20.3*	20.4*
Urea	20.1	20.2*	20.2*	20.5*
Urea + Limus	20.0	20.1	20.2*	20.3*
AN+KN+AMS	20.0	20.2*	20.3*	20.1
ESN	20.1	20.2*	20.2*	20.4*
LSD (α = 0.10)	0.2			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

Table 31. Effect of N source and timing of N application on the concentration of soybean grain protein at three locations in Illinois in 2016. For each location, values in parenthesis represent the concentration of grain protein produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	protein %			
	Yorkville (Unfertilized control= 34.9%)			
AN†	34.9	34.7	34.7	34.6
AMS	35.0	35.0	34.9	34.9
UAN	34.9	34.6	34.6	34.8
Urea	34.8	34.8	34.8	35.0
Urea + Limus	35.0	34.7	34.9	34.7
AN+KN+AMS	34.9	35.0	34.8	34.9
ESN	34.8	34.5	34.9	34.7
LSD (α = 0.10)	NS			
	Champaign (Unfertilized control= 36.3%)			
AN	36.3	36.3	35.9	35.8
AMS	36.2	36.0	36.2	36.1
UAN	36.4	36.1	36.2	36.0
Urea	36.6	36.5	36.5	36.4
Urea + Limus	36.3	36.5	36.3	36.4
AN+KN+AMS	36.4	36.3	36.3	36.4
ESN	36.3	36.6	36.3	36.1
LSD (α = 0.10)	NS			
	Harrisburg (Unfertilized control= 35.9%)			
AN	35.8	35.3	35.0	35.2
AMS	35.7	35.5	35.6	35.5
UAN	35.6	35.4	35.4	35.3
Urea	35.5	35.7	35.3	35.0
Urea + Limus	35.8	35.5	35.4	35.3
AN+KN+AMS	35.7	35.6	35.4	35.5
ESN	35.7	35.5	35.3	35.2
LSD (α = 0.10)	NS			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

THREE YEAR SUMMARY RESULTS AND DISCUSSION

Weather Conditions

Overall, the 2014, 2015, and 2016 growing seasons experienced above average precipitation periodically between the months of April and August depending on the trial location (Table 3). Most noteworthy was June 2015, where all three sites received an amount of precipitation that was between 9.8 and 10.3 cm above the 20-year average. Temperatures during the three years remained relatively close to the 20-year average (Table 3).

Grain Yield and Yield Components

Averaged across the nine site-years, the yield of the control (unfertilized) treatments was 4.29 Mg ha^{-1} (73.2 bu ac^{-1}) (Tables 32 and 33). Nitrogen fertilization using any of the N sources at most of the four application timings increased yield (Tables 32 and 33). All N sources significantly increased yield at the preplant application timing (Tables 32 and 33). Notably, the greatest increases in yield occurred with the preplant applications, specifically with ESN producing a 0.23 Mg ha^{-1} (4.0 bu ac^{-1}) increase, AN a 0.21 Mg ha^{-1} (3.8 bu ac^{-1}) increase, and UAN a 0.20 Mg ha^{-1} increase (3.6 bu ac^{-1}) over the nine site-years (Tables 32 and 33). In particular, AN fertilization led to the most impressive increases in yield at all four application times, ranging from 0.11 to 0.21 Mg ha^{-1} (2.0 to 3.8 bu ac^{-1}) (Tables 32 and 33). Significant yield increases were also apparent with applications of UAN, Urea + Limus, or ESN at V3 and applications of UAN, Urea, Urea + Limus, AN+KN+AMS, or ESN at R1. All N sources provided at R3 significantly increased yield (Tables 32 and 33).

Looking at the individual locations over the nine site-years, variation in the N source and application time that increased yield was apparent. At the northern locations, significant increases in yield occurred at preplant with AN, AMS, UAN, AN+KN+AMS, or ESN (Tables 34 and 35). Significant increases in yield were also made with the application of AN and ESN at the V3 growth stage and AN, Urea + Limus, or AN+KN+AMS at the R1 growth stage (Tables 34 and 35). At the central locations, significant increases in yield were found with the application of all N sources at preplant, except Urea + Limus and ESN, as well as AN+KN+AMS at the V3 growth stage, AMS at the R1 growth stage, and AN, AMS, UAN, Urea + Limus, or AN+KN+AMS at the R3 growth stage (Tables 34 and 35). At the southern locations, significant increases in yield occurred with AN, UAN, Urea + Limus, AN+KN+AMS, or ESN at preplant, and also with Urea + Limus at the V3 growth stage and UAN and Urea + Limus at the R3 growth stage (Tables 34 and 35). The response of select N sources and N applications suggest that the proper fertilization of soybean with N may differ depending on the soil type and environmental conditions. For example, AMS significantly increased yield at the R1 and R3 application timings only at the central location, but not at the northern or southern regions over the nine site-years (Tables 34 and 35). Such results allow growers to fine-tune their N applications to soybean based on their individual needs.

At the northern locations, significant increases in seed weight were generated by supplying any of the N sources at preplant (Table 36). Seed weight was also significantly increased when AN, AMS, UAN, Urea, or AN+KN+AMS was supplied at V3, when Urea + Limus or AN+KN+AMS was supplied at R1, and when Urea was supplied at R3 (Table 36). At the central location, seed weight was significantly increased by all N sources, except UAN, at preplant (Table 36). Seed weight was also significantly increased when AN, Urea, Urea + Limus, or AN+KN+AMS was supplied at V3, when AN, AMS, or Urea + Limus was supplied at R1, and when AN, AMS, UAN, or AN+KN+AMS was supplied at R3 (Table 36). At the southern location, seed weight was significantly increased with the application of UAN, Urea, Urea +

Limus, AN+KN+AMS, or ESN at preplant, as well as AN or Urea + Limus at V3, AN at R1, and AN, UAN, Urea, or AN+KN+AMS at R3 (Table 36). Seed number was less affected than seed weight by N fertilization. At the northern locations, applications of AN at preplant, R1, or R3 and ESN at preplant or V3 significantly increased seed number (Table 37). At the central locations, seed number was significantly increased by applications of UAN at preplant and AN at R3 (Table 37) At the southern locations, seed number was the greatest when averaged over the nine site-years (Table 37). Significant increases in seed number at the southern location were produced by applications of ESN at preplant and applications of Urea + Limus at R1.

Grain quality (oil and protein concentrations) was increased by select N sources and application timings. Grain oil concentration was most often increased by N fertilization at the central and southern locations at the R1 or R3 application timings over the nine site-years (Table 38). Grain protein concentration was only significantly increased by AN supplied at preplant at the northern locations and by Urea + Limus supplied at preplant at the southern locations over the nine site-years (Table 39).

THREE YEAR SUMMARY CONCLUSIONS

The N source ESN supplied at preplant gave the greatest yield increase over the nine site-years. Although, the ESN was not placed below-ground as was the slow-release N sources used by Takahashi et al. (1991), increases in yield were still generated in our studies with a broadcast application. The slow-release capability of the ESN granule may allow for N to be utilized by the soybean plant over a longer period of time, than with the non-coated N sources. The nitrate-containing sources (AN and UAN) also increased yield when supplied at preplant over the nine site-years. Such results are contrary to findings by Gibson and Harper (1985) and Lyons and Earley (1952), who found that nitrate sources were inhibitory to nodule development and function. The positive response of soybean to AN and UAN fertilization may be explained by the greater yield potential of modern soybean varieties, therefore making the nutritional needs of soybean greater, especially in regards to N.

Furthermore, all N applications made at preplant significantly increased yield over the nine site-years. Similar results were found when AN and urea were banded at planting (Osbourne and Riedell, 2006). Applying N fertilizer at planting may provide the soybean with a supply of N before nodules are fully-developed, preventing any N deficiency at the beginning of the growing season. All N sources also significantly increased yield at the R3 growth stage over the nine site-years. Applying supplemental N fertilizer at the beginning of the reproductive stages may delay the soybean from remobilizing N from the vegetative tissues. As Sinclair and de Wit (1976) noted, the remobilization of N is undesirable, especially during the early reproductive development of the soybean, as it will ultimately result in earlier senescence of the plant. Also, according to Zapata et al. (1987), BNF begins to slow at the R5 soybean growth stage, so having an additional supply of N at this time can potentially maximize soybean yield.

Variation in N sources and applications timing that increased soybean yield are likely related to the soil type and environmental conditions of a particular production season. Such results allow growers to fine-tune their N application timings to soybean based on the field location and weather conditions of a growing season. Most notably, during 2016 in Yorkville, supplemental N fertilization failed to increase soybean yield when compared to the yield results of 2014 and 2015. Lack of a response at this location is likely due to the highly productive soil found in this area and little weather-induced N-loss due to the ideal 2016 growing season that the site experienced. Increases in soybean yield were mostly related to an increase in seed weight, and rarely to increases in seed number. Similar results were founded by Salvagiotti et al. (2009), who concluded that maintaining reproductive growth and N uptake throughout the seed filling process could increase both seed weight and yield of soybean.

As higher-yielding soybean varieties are grown, the amount of nutrients that are needed and removed by the crop will also become greater, especially N. While Salvagiotti et al. (2008) determined that 50% of a soybean's N needs can be met through BNF, it is doubtful that the other 50% of N can be provided by the soil and mineralization alone. Because of this, it is unlikely that the "soybean N credit" theory still holds true today and growers should no longer rely on the management practice of applying less N fertilizer to a subsequent corn crop because soybean was grown previously. Knowing this, the use of supplemental N fertilization holds promise to increasing future soybean yields.

THREE YEAR SUMMARY TABLES

Table 32. Grain yield of soybean as influenced by N source and plant growth stage at N application averaged across three Illinois locations in 2014, 2015, and 2016. Values are averaged over three years, three Illinois locations, three varieties, and six replications each year. The unfertilized control averaged 4.29 Mg ha^{-1} (73.2 bu ac^{-1}).

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Mg ha^{-1}			
AN†	4.50*	4.40*	4.40*	4.42*
AMS	4.43*	4.31	4.35	4.40*
UAN	4.49*	4.40*	4.38*	4.38*
Urea	4.44*	4.36	4.37*	4.39*
Urea + Limus‡	4.39*	4.39*	4.39*	4.39*
AN+KN+AMS	4.47*	4.34	4.38*	4.39*
ESN	4.52*	4.40*	4.38*	4.37*
LSD (α = 0.10)	0.08			
	bu ac^{-1}			
AN†	77.0*	75.2*	75.2*	75.6*
AMS	75.7*	73.7	74.4	75.1*
UAN	76.8*	75.2*	74.8*	74.9*
Urea	75.9*	74.4	74.8*	75.0*
Urea + Limus††	75.1*	75.0*	75.1*	75.0*
AN+KN+AMS	76.4*	74.1	74.8*	75.0*
ESN	77.2*	75.2*	74.9*	74.7*
LSD (α = 0.10)	1.3			
Source of Variation	***P > F***			
N Source (S)	<0.0001			
Application Time (T)	<0.0001			
S x T	0.9013			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

‡Urea + Limus and AN+KN+AMS sources were not included in 2014.

Table 33. Changes in soybean grain yield compared to an unfertilized control as influenced by N fertilizer source and plant growth stage at N fertilization in 2014, 2015, and 2016. Values are averaged over three years, three Illinois locations, three varieties, and six replications each year. The unfertilized control averaged 4.29 Mg ha^{-1} (73.2 bu ac^{-1}).

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Δ Mg ha^{-1}			
AN†	0.21*	0.11*	0.11*	0.13*
AMS	0.14*	0.02	0.06	0.11*
UAN	0.20*	0.11*	0.09*	0.09*
Urea	0.15*	0.07	0.08*	0.10*
Urea + Limus‡	0.10*	0.10*	0.10*	0.10*
AN+KN+AMS	0.18*	0.05	0.09*	0.10*
ESN	0.23*	0.11*	0.09*	0.08*
LSD (α = 0.10)	0.08			
	Δ bu ac^{-1}			
AN†	3.8*	2.0*	2.0*	2.4*
AMS	2.5*	0.5	1.2	1.9*
UAN	3.6*	2.0*	1.6*	1.7*
Urea	2.7*	1.2	1.6*	1.8*
Urea + Limus	1.9*	1.8*	1.9*	1.8*
AN+KN+AMS	3.2*	0.9	1.6*	1.8*
ESN	4.0*	2.0*	1.7*	1.5*
LSD (α = 0.10)	1.3			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

‡Urea + Limus and AN+KN+AMS sources were not included in 2014.

Table 34. Grain yield of soybean at three locations in Illinois as influenced by the N source and plant growth stage at N fertilization in 2014, 2015, and 2016. Values are averaged over three years, three Illinois locations, three varieties, and six replications each year. For each location, values in parenthesis represent the unfertilized control yields.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Mg ha^{-1}			
	Northern§ (Unfertilized control= 4.34 Mg ha^{-1})			
AN†	4.64*	4.50	4.54*	4.44
AMS	4.53*	4.41	4.44	4.44
UAN	4.53*	4.48	4.49	4.40
Urea	4.49	4.41	4.36	4.49
Urea + Limus‡	4.40	4.38	4.58*	4.33
AN+KN+AMS	4.51*	4.47	4.56*	4.44
ESN	4.58*	4.53*	4.49	4.46
LSD (α = 0.10)		0.16		
	Central (Unfertilized control= 4.38 Mg ha^{-1})			
AN	4.60*	4.51*	4.49	4.59*
AMS	4.60*	4.48	4.52*	4.57*
UAN	4.62*	4.48	4.45	4.50
Urea	4.60*	4.42	4.46	4.45
Urea + Limus	4.49	4.49	4.42	4.53*
AN+KN+AMS	4.59*	4.53*	4.45	4.52*
ESN	4.56*	4.48	4.47	4.42
LSD (α = 0.10)		0.12		
	Southern (Unfertilized control= 4.12 Mg ha^{-1})			
AN	4.27*	4.19	4.18	4.24
AMS	4.16	4.04	4.09	4.17
UAN	4.33*	4.24	4.19	4.25
Urea	4.22	4.18	4.20	4.22
Urea + Limus	4.28*	4.29*	4.17	4.30*
AN+KN+AMS	4.33*	4.02	4.12	4.19
ESN	4.36*	4.18	4.19	4.22
LSD (α = 0.10)		0.13		

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

‡Urea + Limus and AN+KN+AMS sources were not included in 2014.

§Northern IL, DeKalb in 2014 and 2015, and Yorkville in 2016; Central IL, Champaign; Southern IL, Harrisburg.

Table 35. Changes in soybean grain yield at three locations in Illinois in 2014, 2015, and 2016. Values are averaged over three years, three Illinois locations, three varieties, and six replications each year. For each location, values in parenthesis represent the unfertilized control yields. Positive values are indicative of yield increases and negative values of yield decreases.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	Δ Mg ha^{-1}			
	Northern§ (Unfertilized control= 4.34 Mg ha^{-1})			
AN†	0.30*	0.16*	0.20*	0.10
AMS	0.19*	0.07	0.10	0.10
UAN	0.19*	0.14	0.15	0.06
Urea	0.15	0.07	0.02	0.15
Urea + Limus‡	0.06	0.04	0.24*	-0.01
AN+KN+AMS	0.17*	0.13	0.22*	0.10
ESN	0.24*	0.19*	0.15	0.12
LSD (α = 0.10)	0.16			
	Central (Unfertilized control= 4.38 Mg ha^{-1})			
AN	0.22*	0.13*	0.11	0.21*
AMS	0.22*	0.10	0.14*	0.19*
UAN	0.24*	0.10	0.07	0.12*
Urea	0.22*	0.04	0.08	0.07
Urea + Limus	0.11	0.11	0.04	0.15*
AN+KN+AMS	0.21*	0.15*	0.07	0.14*
ESN	0.18*	0.10	0.09	0.04
LSD (α = 0.10)	0.12			
	Southern (Unfertilized control= 4.12 Mg ha^{-1})			
AN	0.15*	0.07	0.06	0.12
AMS	0.04	-0.08	-0.03	0.05
UAN	0.21*	0.12	0.07	0.13*
Urea	0.10	0.06	0.08	0.10
Urea + Limus	0.16*	0.17*	0.05	0.18*
AN+KN+AMS	0.21*	-0.10	0.00	0.07
ESN	0.24*	0.06	0.07	0.10
LSD (α = 0.10)	0.13			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

‡Urea + Limus and AN+KN+AMS sources were not included in 2014.

§Northern IL, DeKalb in 2014 and 2015, and Yorkville in 2016; Central IL, Champaign; Southern IL, Harrisburg.

Table 36. Effect of N source and timing of N application on soybean seed weight at three locations in Illinois in 2014, 2015, and 2016. Values are averaged over three years, three Illinois locations, three varieties, and six replications each year. For each location, values in parenthesis represent the individual seed weight produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	mg seed^{-1}			
	Northern§ (Unfertilized control= 148.7 mg seed^{-1})			
AN†	154.1*	152.1*	151.0	**149.7**
AMS	153.8*	151.4*	150.9	149.9
UAN	153.2*	152.9*	150.5	149.8
Urea	152.4*	152.7*	148.5	151.6*
Urea + Limus‡	153.0*	151.2	152.8*	150.1
AN+KN+AMS	153.2*	152.2*	152.6*	148.2
ESN	152.3*	149.5	149.7	150.2
LSD (α = 0.10)	2.7			
	Central (Unfertilized control= 155.8 mg seed^{-1})			
AN	160.4*	159.3*	158.2*	158.2*
AMS	158.8*	156.5	160.3*	158.9*
UAN	156.2	157.1	157.7	158.4*
Urea	160.0*	158.5*	157.6	157.8
Urea + Limus	158.6*	160.5*	158.6*	158.0
AN+KN+AMS	159.0*	158.5*	156.6	159.3*
ESN	158.5*	157.3	157.5	157.6
LSD (α = 0.10)	2.3			
	Southern (Unfertilized control= 127.7 mg seed^{-1})			
AN	129.4	132.0*	130.3*	131.0*
AMS	129.1	126.1	128.0	129.5
UAN	131.1*	129.7	129.2	130.1*
Urea	130.5*	129.6	128.9	130.5*
Urea + Limus	131.6*	130.5*	128.0	131.7
AN+KN+AMS	130.6*	127.4	127.4	129.9*
ESN	130.2*	129.1	129.3	129.4
LSD (α = 0.10)	2.2			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

‡Urea + Limus and AN+KN+AMS sources were not included in 2014.

§Northern IL, DeKalb in 2014 and 2015, and Yorkville in 2016; Central IL, Champaign; Southern IL, Harrisburg.

Table 37. Effect of N source and timing of N application on soybean seed number at three locations in Illinois in 2014, 2015, and 2016. Values are averaged over three years, three Illinois locations, three varieties, and six replications each year. For each location, values in parenthesis represent the number of seeds produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	seed m^{-2}			
	Northern§ (Unfertilized control= 2868 seed m^{-2})			
AN†	3056*	2935	3042*	2997*
AMS	2886	2864	2880	2903
UAN	2959	2930	2925	2890
Urea	2919	2884	2966	2931
Urea + Limus‡	2847	2875	2976*	2865
AN+KN+AMS	2929	2909	2970	2913
ESN	3034*	3037*	2964	2964
LSD (α = 0.10)	108			
	Central (Unfertilized control= 2812 seed m^{-2})			
AN	2872	2837	2841	2909*
AMS	2897	2865	2824	2879
UAN	2943*	2858	2850	2816
Urea	2877	2791	2821	2828
Urea + Limus	2830	2803	2800	2872
AN+KN+AMS	2892	2852	2845	2847
ESN	2882	2861	2842	2815
LSD (α = 0.10)	87			
	Southern (Unfertilized control= 3218 seed m^{-2})			
AN	3280	3171	3203	3246
AMS	3213	3229	3191	3203
UAN	3293	3281	3237	3242
Urea	3224	3241	3250	3219
Urea + Limus	3246	3273	3264	3273
AN+KN+AMS	3305	3121	3202	3241
ESN	3340*	3229	3276	3250
LSD (α = 0.10)	90			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

‡Urea + Limus and AN+KN+AMS sources were not included in 2014.

§Northern IL, DeKalb in 2014 and 2015, and Yorkville in 2016; Central IL, Champaign; Southern IL, Harrisburg.

Table 38. Effect of N source and timing of N application on the concentration of soybean grain oil at three locations in Illinois in 2014, 2015, and 2016. Values are averaged over three years, three Illinois locations, three varieties, and six replications each year. For each location, values in parenthesis represent the concentration of grain oil produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	oil %			
	Northern§ (Unfertilized control= 18.1%)			
AN†	18.0	18.0	18.1	18.1
AMS	18.0	18.1	18.2*	18.1
UAN	18.1	18.1	18.1	18.1
Urea	18.0	18.0	18.1	18.1
Urea + Limus‡	18.1	18.0	18.1	18.1
AN+KN+AMS	18.0	18.1	18.1	18.2*
ESN	18.1	18.1	18.1	18.0
LSD (α = 0.10)	0.1			
	Central (Unfertilized control= 19.1%)			
AN	19.0	19.1	19.2*	19.2*
AMS	19.2*	19.2*	19.2*	19.2*
UAN	19.1	19.1	19.2*	19.2*
Urea	19.1	19.1	19.1	19.2*
Urea + Limus	19.1	19.1	19.2*	19.3*
AN+KN+AMS	19.0	19.1	19.2*	19.2*
ESN	19.1	19.0	19.2*	19.1
LSD (α = 0.10)	0.1			
	Southern (Unfertilized control= 19.9%)			
AN	19.9	20.0*	20.0*	20.1*
AMS	20.0*	20.1*	20.1*	20.0*
UAN	19.7	19.9	20.0*	20.2*
Urea	19.9	19.8	20.0*	20.1*
Urea + Limus	19.8	19.8	20.0*	20.1*
AN+KN+AMS	19.8	20.0*	20.1*	20.1*
ESN	20.0*	19.9	20.0*	20.0*
LSD (α = 0.10)	0.1			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

‡Urea + Limus and AN+KN+AMS sources were not included in 2014.

§Northern IL, DeKalb in 2014 and 2015, and Yorkville in 2016; Central IL, Champaign; Southern IL, Harrisburg.

Table 39. Effect of N source and timing of N application on the concentration of soybean grain protein at three locations in Illinois in 2014, 2015, and 2016. Values are averaged over three years, three Illinois locations, three varieties, and six replications each year. For each location, values in parenthesis represent the concentration of grain protein produced by the unfertilized control plots.

	Plant Growth Stage at N Fertilizer Application			
N Source	**Preplant**	**V3**	**R1**	**R3**
	———— protein % ————			
	Northern§ (Unfertilized control= 35.0%)			
AN†	35.2*	35.0	34.9	34.9
AMS	35.0	34.9	34.9	34.9
UAN	35.0	35.0	34.8	34.9
Urea	34.9	35.0	34.9	34.9
Urea + Limus‡	35.0	35.0	35.0	34.8
AN+KN+AMS	34.9	35.0	35.1	34.9
ESN	35.0	34.9	34.8	35.1
LSD (α = 0.10)	0.2			
	Central (Unfertilized control= 34.3%)			
AN	34.5	34.5	34.0	34.2
AMS	34.2	34.1	34.2	34.5
UAN	34.4	34.3	34.2	34.2
Urea	34.4	34.5	34.4	34.3
Urea + Limus	34.5	34.4	34.1	34.2
AN+KN+AMS	34.5	34.3	34.3	34.4
ESN	34.4	34.3	34.3	34.4
LSD (α = 0.10)	NS			
	Southern (Unfertilized control= 33.4%)			
AN	33.4	33.3	33.1	33.3
AMS	33.4	33.2	33.1	33.2
UAN	33.5	33.3	33.4	33.1
Urea	33.4	33.5	33.2	33.1
Urea + Limus	33.6*	33.5	33.2	33.2
AN+KN+AMS	33.5	33.3	33.1	33.2
ESN	33.5	33.3	33.3	33.2
LSD (α = 0.10)	0.2			

*Significantly different than unfertilized control within an application time, $P \leq 0.10$

†AN is ammonium nitrate, AMS is ammonium sulfate, UAN is liquid urea-ammonium nitrate, Urea + Limus is urea treated with the urease inhibitor Limus, AN+KN+AMS is a mixture of ammonium nitrate, potassium nitrate, and ammonium sulfate, and ESN is controlled-release polymer-coated urea.

‡Urea + Limus and AN+KN+AMS sources were not included in 2014.

§Northern IL, DeKalb in 2014 and 2015, and Yorkville in 2016; Central IL, Champaign; Southern IL, Harrisburg.

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