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Pre-Plant Anhydrous Ammonia Placement Consequences on No-Till Versus Conventional-Till Maize Growth and Nitrogen Responses

Péter Kovács,* George E. Van Scoyoc, Thomas A. Doerge, James J. Camberato, and Tony J. Vyn*

ABSTRACT

With the advent of precision guidance systems, maize (*Zea mays* L.) farmers in various tillage systems have more options in pre-plant nutrient banding relative to the intended crop rows. Anhydrous ammonia (NH_3) placement during pre-plant application is of interest because of concerns for possible ammonia toxicity to maize seedlings when high NH_3 rates are applied too close to the seed row and the need to improve plant-nitrogen (N) use efficiencies. Field studies were conducted between 2010 and 2012 near West Lafayette, IN, to compare traditional angled (diagonally) vs. precision-guided parallel NH_3 applications (the latter was offset 15 cm from the future row) in no-till and conventional tillage systems. The NH_3 was injected to depths of about 12 cm at N rates of 145 and 202 kg N ha⁻¹. Maize was planted with additional starter N (20 kg N ha⁻¹) within 6 d of NH_3 application. Neither NH_3 application placement resulted in significant maize seedling mortality. Conventional tillage increased mean grain yields across N rates and placement treatments from 10.6 to 11.6 Mg ha⁻¹. Tillage did not impact reproductive-stage leaf chlorophyll content (SPAD), or whole-plant N content at maturity when NH_3 was parallel applied, but these plant responses were significantly lower in no-till after diagonal application. Lowering the pre-plant N rate to 145 from 202 kg N ha⁻¹ significantly lowered maize whole-plant biomass and N accumulation at maturity with diagonal application, but not when NH_3 was parallel applied.

Today's agriculture faces two major challenges: (i) satisfying the growing food demand of the ever-expanding world population, while (ii) stabilizing or lowering the associated production risks and environmental pollution. Modern maize production relies heavily on N fertilizer use. Anhydrous ammonia is the most concentrated N source (82% N) and is one of the most widely applied N fertilizers in the last few decades in the United States (IFA, 2013) primarily due to its lower cost per unit of N relative to the cost of other N sources.

With the advent of precision guidance systems, maize farmers in various tillage systems have more options in pre-plant nutrient banding relative to the intended crop rows. The first concern in NH_3 placement during pre-plant applications is possible ammonia toxicity to maize seedlings when high NH_3 rates are applied too close in space and time to the future maize rows. Maize farmers in the Midwest region of the United States traditionally apply their pre-plant NH_3 at some degree of angle (i.e., diagonally) to the intended maize rows and subsequently use secondary tillage in an attempt to minimize maize stand loss. Approximately 40 to 70% of spring pre-plant

applied NH_3 is applied at an angle to the future maize row in the region (T. Doerge, unpublished data, 2013). The second concern is the overall goal of improving plant N efficiencies, and testing whether that can be promoted by applying lower overall N rates when the N fertilizer is parallel applied in close and consistent proximity to the maize row. The third concern is one of integrating pre-plant parallel application with no-till planting systems if newly designed coulter-based applicators achieve less soil disturbance than the deep-shank toolbars used in earlier decades.

A new design of shallow NH_3 applicators (John Deere 2510H Nutrient Applicator), recently introduced to the market (John Deere, 2008), is fundamentally different in operation and nutrient placement than the traditional knife-type NH_3 applicators. A single-disk opener system mounted on a high-clearance frame places nutrients at a depth of about 10 to 12 cm instead of the more typical placement depth of 20 to 25 cm. One of the reported advantages of the 2510H applicators is that the reduced soil disturbance provides more opportunity for farmers to apply NH_3 in no-till systems (John Deere, 2013a). Before the commercial development of the Deere 2510H, Hanna et al. (2005) measured higher NH_3 losses with shallow NH_3 placement using a single-disc opener prototype unit compared to traditional knife-type application to deeper

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Abbreviations: %Nel, ear-leaf nitrogen concentration, ACRE, Agronomy Center for Research and Education, DM_{RG} , aboveground biomass production at physiological maturity, GDU_{C} , Celsius degree based growing degree unit, GY_A , grain yield per unit area, HI, harvest index; NH_3 , anhydrous ammonia; NHI, nitrogen harvest index, N_{total} , whole-plant nitrogen uptake at physiological maturity, RTK, real-time kinematic, Sp_{xx} , SPAD readings at xx growth stage, UAN, urea-ammonium-nitrate.

depth. Nutrient-sealing modifications were made since that time to reduce potential NH_3 losses during applications.

Previous studies (Blue and Eno, 1954; Stanley and Smith, 1956; McDowell and Smith, 1958; Sohn and Peech, 1958; Sommer and Christensen, 1992; Hanna et al., 2005) documented that retention of NH_3 in the soil following traditional knife-type injection depends on the depth of application, moisture content of the soil, soil texture, and the amount of soil organic matter. Other studies have concluded that gaseous NH_3 losses were negligible immediately following application even at higher N rates at optimum soil (moisture) conditions when depth of NH_3 placement was 5 cm in medium-textured soils, and 10 cm in coarser-textured soil (Baker et al., 1959; Swart et al., 1971). Optimal soil moisture at the time of application may be more crucial for shallow NH_3 placement, and less optimum soil moisture conditions are more likely in side-dress vs. pre-plant applications.

Although there has been extensive engineering testing in the design of the Deere 2510H applicator (John Deere, 2013a) for the ability to operate in a wide range of soil conditions (such as soil moisture, texture, and different tillage or crop rotation systems), relatively few studies have investigated whether this new applicator improves nutrient use efficiency for N in modern maize production systems. In fact, few replicated field research studies have been conducted using the 2510H (John Deere 2013a) applicator in the United States, and none in Indiana. Results of these studies with the 2510H (John Deere 2013a) are available in graduate theses or in conference proceedings (maize: Sawyer et al., 2009; Stamper, 2009; Fernández et al., 2011; Foster and Mengel, 2012a, wheat [*Triticum aestivum* L.]: Wyckoff, 2009; Foster and Mengel, 2012b). Some of these studies compared the shallow NH_3 placement (~12 cm) with the deep NH_3 placement (20–25 cm; Sawyer et al., 2009; Stamper, 2009). Certainly, growers would like to better understand the possible consequences of shallow NH_3 placements combined with precision guidance.

Placement of N in general, and NH_3 in particular, in close proximity to maize plants has been shown to negatively impact plant growth under some conditions. Sawyer et al. (2009) reported slow maize seedling emergence, severely reduced growth rates, and greater visual damage at higher fertilizer N rates (179 and 224 kg N ha⁻¹), when NH_3 was pre-plant applied—with a high-speed, low-disturbance applicator—directly below future maize rows between 7 and 20 d before planting maize in Iowa. They also observed small but visible reductions in maize growth at the 224 kg N ha⁻¹ rate when NH_3 was fall applied in the same below-row position. The early-season delay in development resulted in reduced plant biomass and grain yield per unit area (GY_A). However, Stamper (2009) in Kansas did not report seedling injuries with the very same method with supplemental irrigation (timing of irrigation was not published).

With traditional applicators, the degree of injury to maize germination and early growth decreased with increasing application depth or increasing time between pre-plant NH_3 application and planting (Colliver and Welch, 1970). Damage to maize seedlings increased with higher N rates. Toxicity was expressed not only in reduced seedling emergence, but also in plant death following emergence and in stunted growth. Shallow NH_3 applicators obviously are limited in their ability

to increase application depth. However, increased horizontal separation of the NH_3 band from the intended maize row and temporal separation between NH_3 application and planting are two ways to enhance crop safety. These two methods were recommended for the shallow nutrient applicator to avoid seedling injuries (Sawyer et al., 2009; Fernández et al., 2011).

Many management factors have been documented that can influence individual plant performance within maize stands; these include planter type (Liu et al., 2004a), delay in seedling emergence and uniformity (Nafziger et al., 1991; Liu et al., 2004b), plant density (Daynard and Muldoon, 1983; Boomsma et al., 2009; Ciampitti and Vyn, 2011; Rossini et al., 2011), low N rates (Boomsma et al., 2009), and uneven plant spacing (Doerge et al., 2002; Lauer and Rankin, 2004; Liu et al. [2004b, 2004c]; Nielsen, 2006). An additional source of plant-to-plant variability can be the placement of N as this factor affects the time required for the developing plant root system to reach plant-available N following banded applications.

Recommendations by agronomists (Wagner and Vasey, 1979; Monsanto Technology Development, 2013; Rankin, 2013; Sawyer, 2013) encourage caution with spring pre-plant NH_3 application; therefore most farmers and especially those without reliable navigation guidance still apply pre-plant NH_3 at some angle (diagonally) to the intended maize row. However, diagonally-applied NH_3 can induce visible band effects throughout the field (Zhang et al., 2008b, 2010a, 2010b) reflecting temporary N deficiency, which can appear as light green strips between the application bands. Diagonal application creates varying distances between maize plants and the nutrient band and thus, depending on soil and environmental factors, maize plants within a row will vary in their access to mineral N from those bands. For example, plants closer to the NH_3 application bands showed advanced development in terms of height and leaf greenness compared to plants farther away from the band in Iowa (Zhang et al., 2008b, 2010a, 2010b). On the other hand, NH_3 placement directly under maize plants (such as the intersection of NH_3 band and plant row in diagonal application) in some cases turned out to be disadvantageous for plant development (Sawyer et al., 2009; Fernández et al., 2011). These early-stage nutrient advantages and disadvantages could result in less uniform plants within the rows and, perhaps, reductions in final GY_A and N uptake.

Tillage system can also be an important factor affecting the uniformity of maize plant growth/development and the uniformity of root access to nutrients (DeFelice et al., 2006). Al-Kaisi and Kwaw-Mensah (2007) found no significant differences between tillage systems on maize yield and N uptake in Iowa during their manure and fertilizer comparison study. Most tillage-derived differences in crop nutrient status were observed early in the growing season. Vetsch and Randall (2004) observed a GY_A benefit with conventional tillage compared to no-till system, but they noted that tillage system had minimal effect on measured maize production parameters and no effect on relative yield performance of various N timing or placement methods. Both Mengel et al. (1982) and Boomsma et al. (2010) found conventional tillage increased grain yield compared to no-till system. The latter study also emphasized the critical importance of maintaining uniform plant heights during vegetative development in no-till maize

for achieving final yields similar to those with conventional tillage (Boomsma et al., 2010).

Because of the utility and decreasing cost, farmers are increasingly adopting real-time kinematic (RTK) correction for GPS guidance which can repeatedly position tractors to the same position, with ± 2 cm precision (John Deere, 2013b). This technology enables farmers to more confidently place their nutrients parallel to, but potentially at a “safe” distance away from, the maize row to provide all plants consistent accessibility to fertilizers. Maize GY_A advantages of the RTK system in precise parallel placement of rows 12 to 13 cm away from pre-plant, coulter-injected urea ammonium-nitrate (UAN) applications at total N rates up to 224 kg N ha^{-1} were previously demonstrated in Indiana (Vyn and West, 2009). In that study, maize plant populations declined and GY_A were reduced (in some cases up to 3.7 Mg ha^{-1}) when maize rows were planted right on top of the UAN bands within 24 h of UAN application to depths of approximately 8 to 10 cm especially in drier soil conditions and on coarser soil.

To date, no research has evaluated and quantified the effects of pre-plant NH_3 application direction, especially diagonal to the future row vs. parallel to maize rows, on maize performance (GY_A , N uptake, etc.). Effects of N fertilizer application direction have only been compared in common bean (*Phaseolus vulgaris* L.), where parallel urea application increased GY_A (Thung et al., 2007), and in wheat, where no directional effect was found with side-dress NH_3 application (Wyckoff, 2009).

The primary objectives of this study were to evaluate whether maize growth, yield, and plant N acquisition responses to tillage systems or applied N rates were affected by the direction of shallow pre-plant NH_3 applications.

MATERIALS AND METHODS

Site Description and Experimental Design

The study was conducted between 2010 and 2012 at Purdue University's Agronomy Center for Research and Education (ACRE) near West Lafayette, IN (40.4853246, -87.0006963). The experiment was established in a maize-soybean [*Glycine max* (L.) Merr.] crop rotation where soybean was managed with no-till practices. Three management factors were investigated in a factorial design with six replications: (i) NH_3 application direction (traditional diagonal NH_3 application to the maize row [at a 15° angle] vs. parallel application, but 15-cm offset from maize row), (ii) tillage systems (conventional tillage and no-till system), and (iii) applied N rates (202 kg N ha^{-1} [N Rate Calculator recommendation for applied cropping system at $\$880 \text{ Mg}^{-1} \text{ NH}_3$ and $\$197.00 \text{ Mg}^{-1}$ maize price level for Indiana [Iowa State University, 2013]] and 145 kg N ha^{-1}). The latter 33% reduction in N rate was chosen to determine whether parallel placement would be more advantageous to maize GY_A and plant N uptake at lower N rates; unfortunately, resources were insufficient to compare more than two N rates. The two NH_3 application direction treatments are referred to as diagonal and parallel NH_3 application, respectively, in rest of the manuscript. Due to the limited area available for this experiment and the constraints of requiring sufficiently wide “border plots” for equipment turning alongside plots with diagonal NH_3 application; treatment assignment followed a randomized complete block design with split-plot arrangement

where NH_3 application direction was the main factor, and tillage systems and N rates were the subplots. Subplots were 9.15 m in width (12 rows) and 68.6 m in length.

The study was conducted on a Chalmers silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll) soil in 2010 and 2012, and on Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll) soils in 2011 with 30 to 40 and 35 to 50 mg kg^{-1} organic matter content, respectively. Both soils involved in the experiment were poorly drained, but systematically tile drained.

Weather Information

Daily minimum and maximum air temperatures, and precipitation information was obtained for the growing seasons from an automated weather station operated by the Indiana State Climate Office located about 1 km from the research sites.

Field Preparation and Planting

Conventionally tilled plots were chisel-plowed to a 25-cm depth the previous fall of the respective growing seasons. The John Deere 2510H nutrient applicator (John Deere, Moline, IL) consists of a toolbar that was three-point hitch mounted on a dual-wheeled tractor. This applicator was used to pre-plant apply NH_3 to a depth of about 12 cm at the assigned N rates and directions relative to future maize rows. The applicator was upgraded and equipped with an a NH_3 Equaply anhydrous delivery system (a NH_3 Company, Elkhart, IL) in 2011 and 2012. Soil moisture conditions were optimal for NH_3 application each year of the study; no visible fumes or strong odors of NH_3 escape were noticed during application. One pass of shallow secondary tillage was done following NH_3 application in conventional-tilled plots to avoid disturbance of the NH_3 band. Maize was planted at $85,000 \text{ seeds ha}^{-1}$ rate using a JD1780 six-row planter (John Deere, Moline, IL) equipped with no-till trash-wheel and coulter combinations. Pioneer 1395XR (comparative relative maturity [CRM] 113 d; DuPont Pioneer, Johnston, IA) and 1567XR (CRM 116 d; DuPont Pioneer, Johnston, IA) hybrids were planted in 2010 and 2011–2012, respectively. Starter fertilizer (10–34–0) was applied at the rate of about 20 kg N ha^{-1} and about $70 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ using the typical placement of 5 cm to the side by 5 cm below the seed at the time of planting. The timing of NH_3 applications and other key maize phenological stages (Abendroth et al., 2011) for the respective years are shown in Table 1.

In-Season Morpho-Physiological Plant Measurements

Intensive individual-plant and plot-level measurements were taken in three of the six replications unless otherwise indicated.

Two “uniformity zones” were selected in every plot from two different rows before seedling emergence for nondestructive in-season measurements on individual plants. Lengths of these zones were 5.3 m in 2010 and 2011, and 10.7 m in 2012. Although date of seedling emergence for each plant was recorded in all uniformity zones, other in-season measurements were performed only on one of the two uniformity zones in each plot during the growing season. Each plant in the uniformity zone targeted for intensive sequential measurements was tagged with a unique barcode.

Table 1. Dates of anhydrous ammonia (NH₃) application, planting, and key maize phenological growth stages for 2010 through 2012 field experiments near West Lafayette, IN.

Variables	2010	2011	2012
NH ₃ application	13–14 Apr.	12 May	12 Apr.
Secondary tillage	16 Apr.	13 May	13 Apr.
Planting	17 Apr.	13 May	18 Apr.
V15	29 June	14 July	2 July
Silking (R1)	12 July	21 July	9 July
Biomass harvest	21 Sept.	–	19 Sept.
Grain harvest	24 Sept.	7 Oct.	2 Oct.

Plant populations were estimated by counting the number of plants in four randomly selected 5.3 m long section of rows in each plot after stand establishment (V3–V4 growth stage). Population assessments were conducted in the center four rows in all six replications.

Leaf chlorophyll content was estimated with a SPAD 502 chlorophyll meter (Minolta Camera Co. Ltd., Osaka, Japan) four times during the season (V10, V15, R1, and R3 stages). Leaf chlorophyll content is closely associated with leaf N content, and, therefore, SPAD readings have routinely been used as a fast and nondestructive assay to estimate leaf N (Dwyer et al., 1991). Readings were taken near the margin in the mid-zone of the youngest fully-expanded leaf before silking, and from the ear-leaf after pollination, similar to previous studies (Blackmer and Schepers, 1995; Binder et al., 2000). Means of three readings were recorded for each plant in the uniformity zones.

Silk emergence (visible silks) and pollen shedding (extrusion of anthers) were recorded daily in the uniformity zones. Accumulated thermal units from planting were derived for each plant according to their recorded silking and tasseling dates via the method described by Gilmore and Rogers (1958) using 10 and 30°C temperature thresholds.

Ear-leaves were removed at silking from 10 consecutive plants outside the uniformity zones to determine nutrient concentrations. Leaves were air-dried at 60°C to constant weight, ground and analyzed for N concentration using the Dumas combustion method by a commercial laboratory (A&L Great Lakes Laboratories, Fort Wayne, IN).

After reaching physiological maturity, 6 (2010) and 10 (2012) consecutive representative plants were harvested in non-border rows outside the uniformity zones to determine aboveground biomass production (DM_{R6}) and plant N uptake. Stover and ears were separated, air-dried at 60°C to constant weight, and weighed. Plant component samples were ground and analyzed for N concentrations similarly to the ear-leaf samples. Nutrient uptake was calculated as the product of biomass and nutrient concentrations of each plant fraction. Harvest index (HI) and N harvest index (NHI) were calculated as the ratios of grain weight and grain N accumulation, respectively, to total plant biomass and N accumulation at maturity. Final biomass harvest was not taken in 2011 due to the destructive effects of a hailstorm event during mid-grain fill.

The center six rows of each plot were machine harvested (JD9400 combine John Deere, Moline, IL); grain weight and moisture content were determined and yields were adjusted to 155 g kg⁻¹ moisture content.

Statistical Analysis

Analysis of variance for measured variables was executed using PROC MIXED procedure with SAS 9.2 software (SAS Institute Inc., Cary, NC). Mean separation was accomplished using the least significant difference method with a $P < 0.05$.

RESULTS AND DISCUSSION

Weather Information

Above normal air-temperatures occurred in all three growing seasons (Fig. 1A–1C) especially during the critical period around kernel set (V15–R2). The rainfall amount was above normal in the first half of the 2010 and 2011 seasons (Fig. 1A, 1B, 1D), while it was below or approximately normal rainfall after that. Excessive early-season rainfall delayed the NH₃ application and planting by a month in 2011, and forecasts for even more rain necessitated a decrease in the time interval between the NH₃ application and planting to just 1 d separation (Table 1). A severe hailstorm on 13 Aug. 2011, resulted in substantial leaf shredding and stem lodging/breakage at the late R3 growth stage. There was a 2 to 3 d interval between NH₃ application and planting in 2010, and a 6-d interval in the much drier spring of 2012. The overall rainfall pattern in 2012 was much different from the first 2 yr of the study (Fig. 1C, 1D). Lower than normal precipitation in the beginning of the season (only 33% of normal rainfall between beginning of April and end of July) was followed by approximately normal rainfall in August and September.

In-Season Observations and Measurements

Among treatments across 3 yr, plant populations differed by a maximum value of 1300 plant ha⁻¹ (Table 2) and plant populations were identical for the two NH₃ application directions. Plant population with parallel NH₃ placement at 202 kg N ha⁻¹ in conventional tillage was slightly lower than plant populations with other application direction × tillage treatment combinations (Table 2). Plant populations were lower in the no-till system in 2011 and 2012 compared to the conventional tillage system within the year × tillage interaction (Table 2). At the 202 kg N ha⁻¹ rate, plant population was only higher with parallel NH₃ placement compared to diagonal NH₃ placement in 2012, within the year × application direction × N rate interaction (Table 2). Detectable differences in yield or N uptake among treatments were not expected from these small plant population changes.

Although previous studies reported substantial injury to single plants, or extended lengths of maize plant rows, when pre-plant NH₃ was used as the N source (Colliver and Welch, 1970; Sawyer et al., 2009; Stamper, 2009), extensive plant damage was not observed in any of the 3 yr regardless of NH₃ application direction (Fig. 2). The primary cause of the apparent seedling emergence failure was not investigated. Poor seedling emergence could be due to planting error (missing seed), non-viable seed, soil disease related death, or ammonium salt toxicity. In addition, the visible “band”-effects associated with plant N deficiencies at various distances from diagonal NH₃ application documented earlier by Zhang et al. (2008b, 2010a, 2010b) were not evident in this experiment. In this case, the lack of a visual “N-deficient band” effect is probably due to the use of starter fertilizer which, at the rate of 20 kg N ha⁻¹,

Fig. 1. Maximum and minimum air temperature (dashed and solid lines, respectively) and their respective 30-yr normal (dotted line) temperatures and daily precipitation (bars) during the growing season in (A) 2010, (B) 2011, and (C) 2012, and (D) monthly precipitation deviation from the 30-yr normal (1981–2010; observed at the Indiana State Climate Office's Station near West Lafayette, IN. The 30-yr normal monthly precipitation indicated at the bottom of panel D. Plant development status (Abendroth et al., 2011) is noted above the graphs of each year: PI—seed planting, Harvest—machine harvest. Hail storm event in (B) 2011 marked with the * symbol.

helped to provide sufficient N for early plant growth (20 kg N ha^{-1} represents the approximate plant N accumulation until V6 growth stage) regardless of the plant distance from the concentrated NH_3 band. The maize root system also can grow large enough to reach the middle of the row by the V6 stage (Hoeft et al., 2000).

Both tillage system and N rate significantly affected SPAD readings at mid-silking (Sp_{R1} ; Table 3). Higher SPAD readings were recorded in plots with conventional tillage and at the higher N rate (Table 4).

Both NH_3 application direction $\times$ tillage system and application direction $\times$ N rate interactions were detected for Sp_{R3} at the 10% probability level (Table 3). The tillage impact for the application direction $\times$ tillage system interaction and the N rate impact in application direction $\times$ N rate interactions, respectively, were significant only in diagonal NH_3 treatments and tended to reflect smaller changes with parallel NH_3 application. When NH_3 application direction was compared within tillage system or N rate, SPAD readings during reproductive stage (Sp_{R3}) were marginally higher in no-till system, and lower in conventional tillage with parallel NH_3 application. Parallel NH_3 application resulted in approximately 1.0 unit higher SPAD readings at the lower N rate during grain fill,

but readings were almost the same with this combination at the higher N rate (202 kg N ha^{-1}). Nitrogen rates, tillage, and year $\times$ N rate interactions had the biggest impact on ear-leaf N concentration ($\%\text{N}_{\text{el}}$; Table 3). Higher $\%\text{N}_{\text{el}}$ at silking were observed in conventional vs. no-tillage plots (Table 4). The year $\times$ N rate interaction revealed that differences in higher $\%\text{N}_{\text{el}}$ with higher N rate was only significant in 2010 and 2011 (Table 5).

Silk emergence was significantly delayed in the no-till system in 2010 and 2012 compared to the conventional tillage system (Table 5). However, delayed silking due to lower N rate was observed only in 2012 (Table 5).

A minimal difference of SPAD readings in plants grown using the two NH_3 application directions is consistent with previous research results (Zhang et al., 2008a, 2009) where authors showed possible limitations of SPAD in identifying moderate N deficiencies; the N levels applied in this study (starter N fertilizer + 145 or 202 kg N ha^{-1}) would not be expected to severely limit crop growth or N uptake. In addition, SPAD readings were taken from the ear-leaf where higher N concentrations are expected to persist longer during grain fill due to its proximity to the sink (Drouet and Bonhomme, 1999, 2004).

Table 2. Anhydrous ammonia application direction × tillage system × N rate, year × tillage systems, and year × application direction × N rate interactions effect on plant population in field experiments conducted in 2010 through 2012.

Year	NH ₃ application direction	Tillage system	N rate	Plant population
			kg N ha ⁻¹	plants ha ⁻¹
<u>Direction × Tillage × N rate</u>				
	Diagonal	No-till	145	80,300ab†
			202	80,300ab
		Conventional tillage	145	81,000a
			202	81,400a
	Parallel	No-till	145	79,300b
			202	80,900a
		Conventional tillage	145	81,600a
			202	80,900a
<u>Year × Tillage systems</u>				
2010		No-till		82,900a
		Conventional tillage		82,900a
2011		No-till		79,600c
		Conventional tillage		80,700b
2012		No-till		78,000d
		Conventional tillage		80,100bc
<u>Year × Direction × N rate</u>				
2010	Diagonal		145	82,700a
			202	83,600a
	Parallel		145	83,200a
			202	82,200ab
2011	Diagonal		145	79,950cde
			202	81,000bc
	Parallel		145	79,200def
			202	80,500cd
2012	Diagonal		145	79,300def
			202	78,000f
	Parallel		145	78,900 ef
			202	79,900cde

† Treatment means with different lowercase letters indicate statistically significant differences within the interaction at $P = 0.05$.

Grain Yield

Yield levels were different in each season primarily due to various weather-related limiting conditions (hailstorm, drought); the mid-August hailstorm in 2011 resulted in approximately 2 Mg ha⁻¹ lower GY_A than 2010 (Table 5). The severe drought of 2012 reduced overall GY_A even more (by approximately 30% compared to previous years' mean yields; Table 5). Higher GY_A was observed in conventional tillage system than in no-till system in each year, but difference between tillage systems was about 1.5 Mg ha⁻¹ in 2010, while only about 0.8 Mg ha⁻¹ in 2011 and 2012 (Table 5). As expected, N fertilizer rate also significantly influenced GY_A (Table 3), but differences between N rates was almost 1.5 Mg ha⁻¹ in 2010 while the same was only about 0.8 Mg ha⁻¹ in 2011 and 2012 (Table 5). Despite the large differences in GY_A between the tillage systems and N rates, GY_A at the lower N rate with parallel NH₃ placement did not differ from GY_A attained with the higher N rate with diagonal NH₃ placement; neither did GY_A with parallel application in the no-till tillage system differ significantly from GY_A attained in conventional tillage with diagonal application. The lower N rate lowered GY_A by

0.8 and 1.2 Mg ha⁻¹ in conventional till and no-till systems, respectively, within the tillage system × N rate interaction; however GY_A for the 145 kg N ha⁻¹ in conventional tillage did not differ significantly from that of the no-till at 202 kg N ha⁻¹ (data not shown).

Higher maize GY_A in conventional tillage than in no-till was previously reported for Indiana by Barber (1971), Mengel et al. (1982), West et al. (1996), and Boomsma et al. (2010), and for other Corn Belt states by Fink and Wesley (1974), Huggins and Pan (1993), Vetsch and Randall (2004), and Bos (2012). Proportional differences between tillage systems and N rates were smaller in 2011 and 2012 relative to 2010, presumably as a result of plant growth/grain fill limitations from the hailstorm damage in 2011, and drought stress in 2012 (Eck, 1984; Bennett et al., 1989). The higher leaf chlorophyll content during the grain fill period in both low N rate and no-till treatments with parallel NH₃ application (Sp_{R3}; Table 6) presumably contributed to slightly higher GY_A compared to the corresponding treatments that were applied diagonally.

Fig. 2. Effect of anhydrous ammonia (NH_3) diagonal placement on early plant development near the NH_3 band. Flags indicate NH_3 band and maize row intersection. (A) Stunted plant growth was randomly observed near NH_3 band, but not at every (B) NH_3 band intersection.

Biomass and Nutrient Accumulation

As expected, the higher N rate resulted in higher DM_{R6} values (Table 6). The lower N rate significantly reduced DM_{R6} in plots with diagonal NH_3 application, but there was no effect of N rate on DM_{R6} with parallel NH_3 application (Fig. 3).

Tillage and N rate had a significant impact on HI at the 5% probability level, while the application direction $\times$ N rate, and year $\times$ N rate interactions were significant at the 10% probability level (Table 3). The HI was significantly higher at the 202 kg N ha^{-1} rate within diagonal NH_3 placement, while

HI did not differ between N rates in plots with parallel NH_3 placement (Fig. 4). However, the observed variation of HI did not result in any statistical differences in GY_A at harvest (Table 4). Conventional tillage significantly increased HI in diagonal NH_3 placement, but tillage had no effect with parallel NH_3 application. Mean HI was 0.50 in 2010, and about 0.44 in 2012 (data not shown).

The direction of N placement was found to be crucial at the lower N rate, where parallel NH_3 application resulted in almost 12% higher N_{total} , while at the higher N rate differences

Table 3. Analysis of variance significance levels for treatment effects on various plant and whole plot measurements in 2010 to 2012 field experiments near West Lafayette, IN. Variables include plant population (PLP), silk emergence (Si), ear-leaf N concentration at silking ($\%\text{N}_{\text{el}}$), SPAD readings at R1 and R3 stages (SP_{R1} , SP_{R3}), combine harvested yield (GY_A), total biomass production (DM_{R6}), grain harvest index (HI), grain nitrogen concentration ($\%\text{N}_{\text{gr}}$), total whole-plant nitrogen uptake (N_{total}), and nitrogen harvest index (NHI). Data marked with ‡ indicates that statistical analysis were based on six replications; otherwise it was based on three replications.

Variables	2010–2012						2010, 2012				
	PLP	Si	$\%\text{N}_{\text{el}}$	SP_{R1}	SP_{R3}	GY_A ‡	DM_{R6}	HI	N_{total}	$\%\text{N}_{\text{gr}}$	NHI
Year (Y)	***	*	**	**	*	***	***	*	ns†	***	‡
Direction (D)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Tillage (TS)	**	***	**	**	***	***	ns	*	ns	ns	ns
N Rate (NR)	ns	‡	***	**	***	***	***	**	***	ns	**
D $\times$ TS	ns	ns	ns	ns	‡	ns	*	ns	ns	ns	‡
D $\times$ NR	ns	ns	ns	ns	‡	ns	**	‡	**	ns	‡
TS $\times$ NR	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
D $\times$ TS $\times$ NR	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y $\times$ D	ns	ns	ns	ns	ns	ns	ns	ns	ns	‡	ns
Y $\times$ TS	*	***	ns	ns	ns	*	ns	ns	ns	ns	ns
Y $\times$ D $\times$ TS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y $\times$ NR	ns	*	**	ns	ns	**	ns	‡	ns	*	ns
Y $\times$ D $\times$ NR	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
Y $\times$ TS $\times$ NR	ns	ns	ns	ns	ns	ns	ns	ns	‡	ns	ns
Y $\times$ D $\times$ TS $\times$ NR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

† ns, not significant.

‡ Significant at $P = 0.1$.

Table 4. Effect of shallow anhydrous ammonia placement on plant population, silk emergence (Si), ear-leaf N concentration (%N_{el}), SPAD reading at R1 and R3 (SP_{R1}, SP_{R3}), and combine harvested grain yield (GY_A) using different tillage systems and N rates in field experiments conducted in 2010 through 2012. Data marked with ‡ indicates that statistical analysis were based on six replications otherwise it was based on three replications.

Treatment	Population plants ha ⁻¹	Si GDU°C	%N _{el} g kg ⁻¹	SP _{R1}	SP _{R3}	GY _A ‡ Mg ha ⁻¹
Application direction (D)						
Diagonal	80,700†	794	27.1	52.4	51.6	10.96
RTK	80,600	796	27.4	52.7	52.2	11.28
Tillage system (TS)						
No-till (NT)	80,200b	815a	26.8b	51.9b	51.1b	10.62b
Conventional till (T)	81,200a	775b	27.7a	53.2a	52.7a	11.61a
N rate (NR)						
145 kg N ha ⁻¹	80,500	798	26.5b	52.0b	50.9b	10.64b
202 kg N ha ⁻¹	80,900	791	27.9a	53.1a	52.8a	11.59a
D × TS						
Diagonal-NT	80,300b	813a	26.6b	51.5b	50.5b	10.52c
Parallel-NT	80,100b	816a	27.0ab	52.4ab	51.7ab	10.73bc
Diagonal-T	81,200a	774b	27.5ab	53.3a	52.7a	11.39ab
Parallel-T	81,200a	775b	27.8a	53.1ab	52.6ab	11.82a
D × NR						
Diagonal-145N	80,600	800a	26.4b	51.6b	50.3c	10.42c
Parallel-145N	80,400	796ab	26.7b	52.4ab	51.6bc	10.86bc
Diagonal-202N	80,800	788b	27.7a	53.1a	52.9ab	11.49ab
Parallel-202N	80,900	795ab	28.1a	53.0ab	52.7a	11.69a

† Means within each main factor or interaction followed by different lowercase letters are different at $P = 0.05$.

were not observed in N_{total} in the application direction × N rate interaction (Fig. 3).

Significantly higher grain N concentrations (%N_{gr}) were observed in conventionally tilled plots in 2010, while no difference was observed between tillage systems in 2012 (Tables 3 and 5).

Year × application direction × N rate interaction significantly impacted N harvest index (NHI; Table 3); and NH₃ application direction × tillage system and application direction × N rate interactions for NHI were also significant at the 10% probability level ($P = 0.09$ and $P = 0.09$ respectively;

Table 5. Effect of shallow anhydrous ammonia placement on ear-leaf N concentration at mid-silking (%N_{el}), on silk emergence (Si), combine harvested grain yield (GY_A), grain N concentration (%N_{gr}), and nitrogen harvest index (NHI) using different tillage systems and N rates in field experiments conducted in 2010 through 2012. Data marked with ‡ indicates that statistical analysis were based on six replications otherwise it was based on three replications.

Treatment	%N _{el} g kg ⁻¹	Si GDU°C	GY _A ‡ Mg ha ⁻¹	%N _{gr} g kg ⁻¹	NHI kg kg ⁻¹
Year × N rate					
2010-145N	24.8c†	812 ab	12.77b	11.7b	
2010-202N	27.5b	814ab	14.19a	12.0b	
2011-145N	29.1b	768c	11.08c	—	
2011-202N	30.3a	767c	11.86b	—	
2012-145N	25.8c	814a	8.08e	16.1a	
2012-202N	25.9c	793bc	8.72d	15.6a	
Year × Tillage system					
2010-NT		826a	12.79b	11.2c	
2010-T		800b	14.16a	12.5b	
2011-NT		773c	11.06c	—	
2011-T		762c	11.88b	—	
2012-NT		846a	8.02e	16.0a	
2012-T		761c	8.79 d	15.7a	
Year × Direction × N rate					
2010-Diagonal-145N					0.56a
2010-Diagonal-202N					0.58a
2010-Parallel-145N					0.58a
2010-Parallel-202N					0.61a
2012-Diagonal-145N					0.43b
2012-Diagonal-202N					0.56a
2012-Parallel-145N					0.52ab
2012-Parallel-202N					0.53ab

† Means within each main factor or interaction followed by different lowercase letters are different at $P = 0.05$.

Fig. 3. Effect of anhydrous ammonia placement and applied N rates on whole-plant biomass production (DM_{R6}) and N uptake (N_{total}). Error bars present standard errors. Different lowercase letters indicate statistically significant differences between treatments.

Fig. 4. Effect of anhydrous ammonia placement and applied N rates on grain harvest index (HI) and nitrogen harvest index (NHI). Error bars present standard errors. Different lowercase letters indicate statistically significant differences between treatments.

Table 3). Within year $\times$ application direction $\times$ N rate interaction treatment responses did not differ in 2010 (Table 6). However, within the diagonal NH_3 placement in 2012 the 145 kg N ha⁻¹ rate lowered NHI by about 22% compared to the 202 kg N ha⁻¹ rate. Similar to HI, NHI did not differ between tillage systems with parallel NH_3 placement, but differed with diagonal NH_3 placement in the application direction $\times$ tillage system interaction (Table 6). In the direction $\times$ N rate interaction, lowering N rate did not impact NHI with parallel NH_3 placement, while NHI was significantly reduced with diagonal NH_3 application (Fig. 4).

The advantages of parallel NH_3 application on HI between tillage systems and N rates were also observed in leaf chlorophyll content during grain fill (Sp_{R3} ; Table 4), suggesting greater photosynthetic activity during reproductive stages and contribution to ear dry matter accumulation (Tollenaar and Lee, 2010). Overall, HI was lower in 2012 compared to 2010 (Table 5) due to heat and drought stress that reduced kernel set (data not shown) during pollination in 2012. Similar results were reported

by Westgate and Boyer (1985), NeSmith and Ritchie (1992), Schussler and Westgate (1994), and Roth et al. (2013).

The absence of application direction effects on N_{total} at the higher N rate is presumably because this N rate supplied adequate N to all plants regardless of proximity to the NH_3 bands. Greater plant N accumulation was observed with parallel NH_3 placement in the no-till system, and at the 145 kg N ha⁻¹ rate, compared to the same direction and N rate treatments with diagonal NH_3 application. Also, reducing the N rate had less deleterious impact on plant DM_{R6} and N_{total} when NH_3 was parallel applied. Similarly, the reduced N rate had less impact on ear-leaf chlorophyll content (Sp_{R3}) in parallel NH_3 placement treatments during maize reproductive growth (Table 4). The smaller impact of N rate reduction with parallel NH_3 application suggests that the risk of yield loss from reduced N rates is less when N is precision applied in a consistent and “safe” proximity to maize rows.

However, in 2012 N accumulations ($\%N_{cl}$, N_{total}) with parallel NH_3 application were lower in the conventional tillage system compared to no-till system (data not shown). Parallel NH_3 application at 202 kg N ha⁻¹ rate resulted also in lower $\%N_{cl}$ and N_{total} compared to the lower N rate (data not shown). These reductions in N utilization suggests that the 15-cm horizontal NH_3 band displacement from the maize row may have been too close in conventional tillage and at the 202 kg N ha⁻¹ rate during the dry season of 2012.

SUMMARY AND CONCLUSION

Overall maize plant damage was minimal from shallow pre-plant NH_3 placement in either no-till or conventional tillage systems, even when application occurred within 6 d of planting. More damage may have occurred if NH_3 -N had been injected right under the future maize row, as in other studies (Sawyer et al., 2009; Fernández et al., 2011).

The RTK-guided parallel NH_3 application improved plant N status during reproductive growth ($\%N_{cl}$, Sp_{R3} ; Table 4), and at the low N rate N uptake at maturity (N_{total} ; Table 6, Fig. 3), relative to the traditional diagonal pre-plant NH_3 application. Parallel, but offset from the row NH_3 placement,

Table 6. Effect of shallow anhydrous ammonia placement on whole season aboveground biomass production (DM_{R6}), harvest index (HI), total whole-plant N uptake (N_{total}), and nitrogen harvest index (NHI) using different tillage systems and N rates in 2010 and 2012.

Treatment	DM_{R6} Mg ha ⁻¹	HI kg kg ⁻¹	N_{total} kg ha ⁻¹	NHI kg kg ⁻¹
Application direction (D)				
Diagonal	21.4†	0.46	254	0.53
Parallel	22.1	0.48	263	0.56
Tillage systems (TS)				
No-till (NT)	21.7	0.46b	255	0.54
Conventional till (T)	21.8	0.49a	262	0.56
N Rate (NR)				
145 kg N ha ⁻¹	20.6b	0.45b	240	0.53b
202 kg N ha ⁻¹	23.099a	0.49a	277	0.57a
D $\times$ TS				
Diagonal-NT	20.8	0.44b	248	0.51b
Parallel-NT	22.6	0.47ab	262	0.56ab
Diagonal-T	22.0	0.48a	260	0.56a
Parallel-T	21.6	0.49ab	264	0.56ab

† Means within each main factor or interaction followed by different lowercase letters are different at $P = 0.05$.

only marginally increased GY_A compared to the diagonally placed treatments— $<0.45 \text{ Mg ha}^{-1}$. Yield increases with parallel placement compared to diagonal placement were greatest in the no-till system and the lowest N rate (145 kg N ha^{-1}).

We suggest that application of starter fertilizer, which is still common in Indiana, may have decreased the differences in response between the directional treatments. Larger differences, and higher benefits, would be expected from parallel pre-plant NH_3 placement compared to diagonal application if maize is planted without starter N. However, we are still concerned about the spatial-temporal separation between NH_3 application and planting especially at high N rates (more than 200 kg N ha^{-1}). Further research should determine the “safe” distance of shallow spring pre-plant NH_3 application (especially at high rates) from intended maize rows where yield benefits are still observed, but where crop stunting can be avoided due to dry conditions following N applications. Future studies are also warranted to identify the minimum time interval between NH_3 application and maize planting with different NH_3 placements relative to maize rows on less forgiving soils.

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