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Urea Fertilizer Placement Impacts on Corn Growth and Nitrogen Utilization in a Poorly-Drained Claypan Soil

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Abstract

Practices to increase nitrogen (N) use efficiency (NUE) include selecting appropriate N fertilizer sources and application methods, but minimal research has focused on these practices in poorly-drained claypan soils which are prone to N loss. This research assessed the impact of different urea fertilizer placement practices on corn (*Zea mays* L.) production and N utilization in a poorly-drained claypan soil. Field trials were conducted in 2014 and 2015 in Missouri. Treatments consisted of pre-plant deep banding (20 cm) urea at 202 kg N ha^{-1} or urea plus a nitrification inhibitor (NI) (nitrapyrin) compared to pre-plant urea broadcast surface-applied or incorporated to a depth of 8 cm. In 2014, incorporating urea, deep banding urea, and deep banding urea plus NI had higher yields (> 10%) of corn compared to the control with grain yields ranging from 13.73 to 14.05 Mg ha^{-1}. In 2015, grain yields were lower than in 2014, ranging from 4.1 to 7.9 Mg ha^{-1}. Deep placing banded urea with a NI yielded an increase in grain yield up to 48% compared to the other treatments. Rainfall amounts were higher in 2015, which could have resulted in poorer root growth and greater N loss in deep banded treatments. In 2014, deep banding urea with a NI produced the highest NUE. Similar to NUE, silage tissue N concentrations in 2014 were greater with deep banded urea plus NI, while in 2015 silage tissue N concentrations were higher with surface applied urea. The results suggest that urea fertilizer incorporation including deep banding may improve corn grain production, N uptake, and NUE, but response was affected by climatic conditions. The addition of an NI may be an important safeguard when deep banding urea in years with excessive precipitation.

Keywords: nitrogen use efficiency, deep banding, nitrification inhibitor, urea, nitrogen uptake

1. Introduction

1.1 Nitrogen Management of Poorly-Drained Soils

Nitrogen fertilizer management strategies to increase NUE and corn production have focused on enhancing plant N availability at critical growth stages and minimizing environmental N losses. These management strategies have included changes in crop genetic traits (Hirel et al., 2011), N fertilizer sources (Nelson et al., 2008), timings and methods of fertilizer application (Nash et al., 2013), and the spatial placement of N fertilizer in soil (Drury et al., 2006) or across agricultural fields (Motavalli et al., 2012; Roberts et al., 2012).

In poorly-drained soils, such as claypan soils, there is a high potential for N loss through denitrification which can reduce the available N that can be retrieved by the plant and increase loss to the environment (Nash et al., 2012). Claypans usually are situated 20 to 40 cm below the soil surface (Jung et al., 2006) and encompass an area of approximately 4 million ha across Missouri, Illinois, and Kansas in the Midwestern U.S. (Anderson et al., 1990).

Research on a poorly-drained claypan soil in Missouri has indicated that strip tillage and deep banding of N fertilizer to a depth of 15 cm increased corn yields 1.57 to 5.39 Mg ha^{-1} compared to no-till, broadcast surface application of N fertilizer (Nash et al., 2013). Lehrsch et al. (2000) observed a 6% increase in tissue N concentration in corn silage with banded N fertilizer compared to a broadcast N application. This can be attributed to the higher concentration of nutrients within the root zone with banded fertilizer compared to the lower but more uniformly distributed nutrient concentrations resulting from broadcasting the fertilizer (CAST, 2004). Reeves and Touchton (1986) observed that deep banding urea fertilizer in the tillage row produced the highest corn yield over a three-year study.

Nitrification inhibitors can reduce N loss by slowing down the nitrification process, which converts ammonium to nitrite and then nitrate (Pfab et al., 2012). Reductions in nitrification rates can lower environmental nitrate loss by processes such as nitrate leaching and denitrification thereby increasing N availability to plants (Di & Cameron, 2002; Ferguson et al., 2003).

1.2 Research Needs and Objective

Little research has examined the effectiveness of deep banding N fertilizers and combining that deep placement with a NI in poorly-drained soils. In a well-drained soil, Reeves and Touchton (1986) observed no increase in grain yield when a NI was added to deep placed urea at the time of subsoiling. Therefore, it is important to determine in poorly-drained claypan soils whether or not coupling NIs with deep placement of urea can increase crop production as compared to other urea placement practices. The objective of this research was to assess the impact of different urea fertilizer placement practices, including deep banding with and without a NI, on corn production and crop N utilization in a poorly-drained claypan soil.

2. Method

2.1 Site Location and Experimental Design

This study was conducted in 2014 and 2015 in Northeast Missouri at the University of Missouri Greenley Memorial Research Center (40°1′17″ N, 92°11′24.9″ W) near Novelty on a poorly-drained Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs). The claypan subsurface layer at this research location has been observed to be as shallow as 31 cm (Nash et al., 2012). Daily precipitation data were obtained from a nearby automated weather station located at the Greenley Center.

Two different field locations were used in 2014 and 2015. Experimental plots were planted with a corn (*Zea mays* L.) hybrid, DeKalb 61-88, in fields with soybean (*Glycine max* L. Merr.) the previous year. Plots were approximately 3 by 61 m and contained four rows of corn. Planting was done with a John Deere 7000 planter (Deere and Co, Moline, IL) on 76 cm row spacing at 79,000 seeds ha^{-1}. Planting and harvest dates as well as other management practices are listed in Table 1. The experimental design was a randomized complete block with five replications. Treatments consisted of a non-treated control, urea deep banded (UDB) at a depth of 20 cm, urea deep banded (20 cm) plus a nitrification inhibitor (UDB+NI), urea incorporated after surface broadcast application (UAA) at a depth of approximately 8 cm, and urea broadcast surface applied after incorporation (USA).

Table 1. Field information and management operations in 2014 and 2015

Year	Field information and management	Date and/or rate
2014	N application	9 May
	Planting date	9 May
Herbicide		13 May
	S-metolachlor†	1.48 kg ha^{-1}
	Atrazine‡	1.48 kg ha^{-1}
	Mesotrione§	0.19 ha^{-1}
	Glyphosate [N-(phosphonomethyl)glycine	0.87 kg ha^{-1}
	Topramezone¶	11 Jun/0.05 kg ha^{-1}
Fungicide		10 Jul
	Propiconazole#	0.11 kg ha^{-1}
	Azoxystrobin††	0.13 kg ha^{-1}
	Harvest Date	8 Oct.
2015	N application	30 Apr.
	Planting date	30 Apr.
Herbicide		2 Jun.
	S-metolachlor	1.19 kg ha^{-1}
	Glyphosate [N-(phosphonomethyl)glycine	1.19 kg ha^{-1}
	Mesotrione	0.12 kg ha^{-1}
	Harvest Date	22 Sept.

Note. † (2-Chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acetamide).

‡ (2-Chloro-4-ethylamino-6-isopropylamino-s-triazine).

§ (2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione).

¶ (2-methyl-4-(methylsulfonyl)phenyl](5-hydroxy-1-methyl-1H-pyrazol-4-yl)methanone).

(1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1,2,4-triazole).

†† (Methyl (2*E*)-2-(2-{[6-(2-cyanophenoxy)pyrimidin-4-yl]oxy}phenyl)-3-methoxyacrylate).

All urea treatments were applied at 202 kg N ha^{-1}. The NI (Instinct II®, Dow AgroSciences, Indianapolis, IN) was applied at 2.7 L ha^{-1}. The active ingredient in the NI was nitrapyrin (2-chloro-6-(trichloromethyl) pyridine).

The deep banded N fertilizer treatments were applied using a custom-designed strip-till conservation C-jet unit (Advance, MO). The UDB and UDB+ NI treatments were banded to a depth of 20 cm below the planted row using a Montag (Montag Manufacturing, Inc., Emmetsburg, IA) dry fertilizer air delivery system. After the banded fertilizer application, the entire soil surface was surface-tilled with a field cultivator (John Deere 1000, Moline, IL) to remove the possible physical effects of strip tillage on crop response among treatments.

2.2 Soil Sampling and Analytical Procedures

The initial soil properties for each year (Table 2) were determined from analysis of soil samples taken at 0-15, 15-30, and 30-45 cm depths from the non-treated control plots in all the five replicates. Samples were taken using a stainless steel push probe with four subsamples per plot composited to make one sample. All soil samples were air-dried and ground to pass through a sieve with 2 mm openings. The initial soil samples were analyzed by the University of Missouri Soil and Plant Testing Laboratory using standard soil testing procedures (Nathan et al., 2006). Soil bulk density was determined using the core method (Blake et al., 1986).

Table 2. Means (± 1 standard deviation) of selected initial soil properties in 2014 and 2015

Soil properties	Depth (cm)		
	0-15	15-30	30-45
2014			
pH (0.01 M $CaCl_2$)	6.7 ± 0.1	6.0 ± 0.4	5.0 ± 0.2
Neut. acidity ($cmol_c$ kg^{-1})	0.4 ± 0.2	2.4 ± 0.9	7.0 ± 1.5
Organic matter (g kg^{-1})	28.2 ± 2.8	21.4 ± 1.8	22.4 ± 1.9
Bray I P (kg ha^{-1})	86 ± 14	17 ± 3	17 ± 12
Exc. Ca (kg ha^{-1})	5509± 500	4985 ± 502	6182 ± 375
Exch. Mg (kg ha^{-1})	404 ± 102	518 ± 189	1205 ± 206
Exch. K (kg ha^{-1})	325± 41	167 ± 13	225 ± 23
CEC ($cmol_c$ kg^{-1})	14.6 ± 1.5	15.6 ± 2.3	25.6 ± 2.9
Bulk density (g cm^{-3})	1.02 ± 0.09	1.24 ± 0.10	1.34 ± 0.05
Total N (g kg^{-1})	1.80 ± 0.10	1.33 ± 0.21	1.18 ± 0.07
Total organic C (g kg^{-1})	19.16 ± 2.37	11.54 ± 0.94	10.70 ± 1.08
2015			
pH (0.01 M $CaCl_2$)	6.1± 0.1	5.9 ± 0.2	4.8 ± 0.3
Neut. acidity ($cmol_c$ kg^{-1})	1.2 ± 0.3	1.8 ± 0.6	6.4 ± 2.0
Organic matter (g kg^{-1})	25.8 ± 1.3	17.8 ± 2.6	20.6 ± 3.7
P Bray I (kg ha^{-1})	79 ± 41	9 ± 5	8 ± 1
Exch. Ca (kg ha^{-1})	4111 ± 2571	4224 ± 658	3851 ± 700
Exch. Mg (kg ha^{-1})	372 ± 40	358 ± 114	521 ± 140
Exch. K (kg ha^{-1})	306 ± 28	105 ± 16	104 ± 15
CEC ($cmol_c$ kg^{-1})	12.1 ± 0.9	12.7 ± 2.4	17.1 ± 4.1
Bulk density (g cm^{-3})	1.11 ± 0.02	1.30 ± 0.07	1.52 ± 0.03
Total N (g kg^{-1})	1.18 ± 0.65	0.92 ± 0.06	0.87 ± 0.13
Total organic C (g kg^{-1})	16.03 ± 1.33	8.38 ± 0.87	7.53 ± 1.64

2.3 Plant Tissue Characterization and Yield Determinations

Stand counts for the two inner rows of each plot were recorded each year over a row length of 15.2 m. Corn silage was harvested at physiological maturity by cutting plants from 3.1 m of one corn row and obtaining the total wet weight of the plants using a hanging scale. These plants were then chopped using a mechanized brush chopper (Vermeer Corp., BC700XL, Pella, IA) and subsamples were collected to determine silage moisture for adjusting calculated silage yield on a dry weight basis and for tissue analysis. Silage samples were dried at 70 °C and ground in a Wiley-Mill (Swedesboro, NJ) to pass through a 1 mm sieve.

Total N in the tissue was analyzed using the combustion method with a total carbon-nitrogen analyzer (LECO Corp., Township, Michigan). Tissue N concentration and silage yield were used to calculate N uptake and subsequently the apparent N recovery efficiency (Baligar et al., 2001). Apparent N recovery efficiency is one measure of N use efficiency (NUE) and was calculated using the equation:

$$\text{NUE (\%)} = ((\text{N uptake}_{(\text{treatment})} - \text{N uptake}_{(\text{control})})/\text{N applied}) \times 100 \quad (1)$$

Corn grain yields were determined using a plot combine (Wintersteiger Delta, Salt Lake City, UT) that harvested the two center rows in each plot. All grain yields were adjusted to 150 g kg^{-1} moisture. Grain samples were collected from each plot for determination of test weight, grain moisture (Harvest Master, Logan, UT), and analysis of starch, oil, and protein concentration (Foss 1241 Infratec, Eden Prairie, MN).

2.4 Statistical Analysis

Analysis of variance (ANOVA) was performed using PROC GLM on grain yields, grain moisture, N uptake, and NUE for each year using the Statistical Analysis Software (SAS) v9.4 (SAS Institute, 2014). Fischer's Protected LSD at $P < 0.10$ was used to separate means.

3. Results

3.1 Precipitation

Cumulative rainfall amounts for the 2014 and 2015 growing seasons were 705 and 839 mm, respectively (Figures 1A and 1B). The average ten-year precipitation amount from 2000 to 2010 during the growing season (from April through September) was 660 mm (Nash et al., 2012). The cumulative rainfall during the 2014 growing season exceeded this ten-year average by 45 mm (7%). In 2015, the cumulative rainfall exceeded the ten year average by 179 mm (27%) and was especially high at the beginning of the growing season resulting in visually observed soil waterlogging.

3.2 Corn Plant Populations and Silage and Grain Yields

There were no significant treatment effects on observed corn plant population (data not shown). The mean plant population was 69,240 plants ha^{-1} in 2014 and 75,230 plants ha^{-1} in 2015. Grain yields due to the treatments varied between 2014 and 2015, possibly due to differences in rainfall distribution since 2015 had a very wet spring (Figure 2). In 2014, corn grain yields ranged from 12.1 to 14.1 Mg ha^{-1} (Figure 2). Deep banded urea with and without a NI provided a 9 and 8% increase in yield, respectively, compared to the USA treatment. The UAA treatment had a 7% increase compared to the USA treatment.

In 2015, grain yields were much lower for all treatments compared to 2014 (Figure 2). Grain yields in 2015 ranged from 4.1 to 7.9 Mg ha^{-1} (Figure 2). As expected, the NTC treatment resulted in the lowest yield at 4.1 Mg ha^{-1}. The UDB+NI treatment increased yields compared to UDB by approximately 30%. The USA treatment produced grain yields of 7.4 Mg ha^{-1} which was similar to the UAA treatment at 6.5 Mg ha^{-1}.

In 2014, silage yields ranged from 43 Mg ha^{-1} in the NTC to approximately 55 Mg ha^{-1} for UDB+NI (Figure 3). All treatment means were significantly greater than the NTC treatment, but none of the fertilizer placement treatments were significantly different from each other in silage yield (Figure 3).

Silage yields were lower in 2015 compared to 2014 (Figure 3). In 2015, silage yields ranged from 18 Mg ha^{-1} in the NTC to 27 Mg ha^{-1} in the USA (Figure 3). Surface applying urea during wetter soil conditions increased silage yields 4 to 22% compared to the other N placement treatments. Mean silage yield for USA was significantly higher than for NTC and UDB, but was not significantly different from the UAA and UDB+NI plots.

3.3 Plant N

In 2014, plant N concentrations in the corn silage tissue ranged from 0.73% in the NTC to 1.21% in the UDB+NI (Table 3). The mean silage tissue N concentration for UDB+NI was significantly higher than the USA and UAA treatments. Every treatment except for UAA had tissue N concentrations that were significantly greater than that of the NTC treatment.

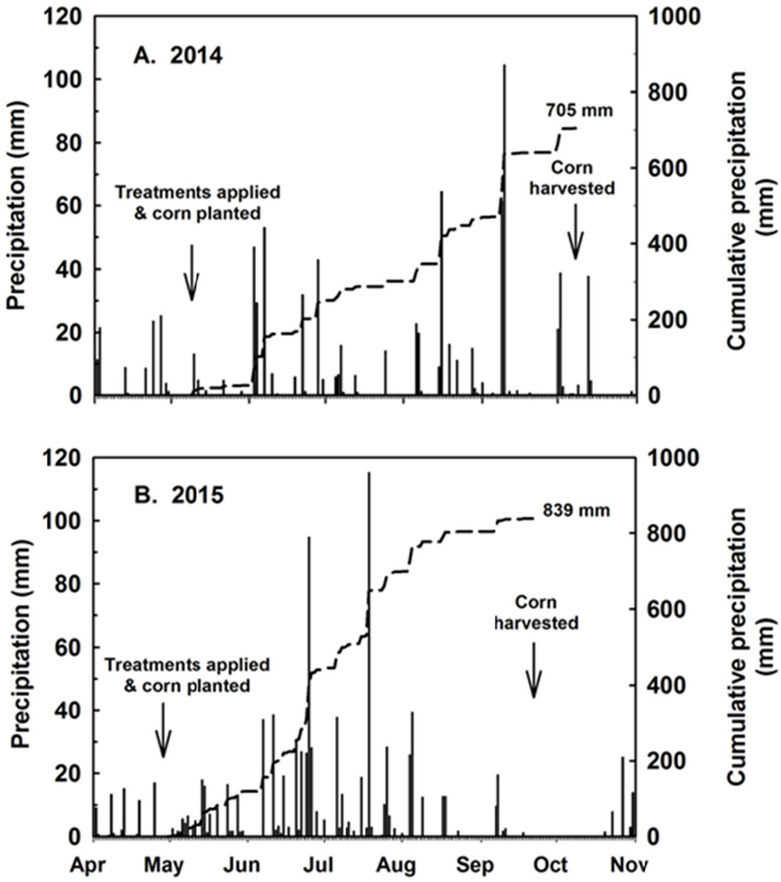

Figure 1. A&B. Daily (bars) and cumulative precipitation (line) in (A) 2014 and (B) 2015

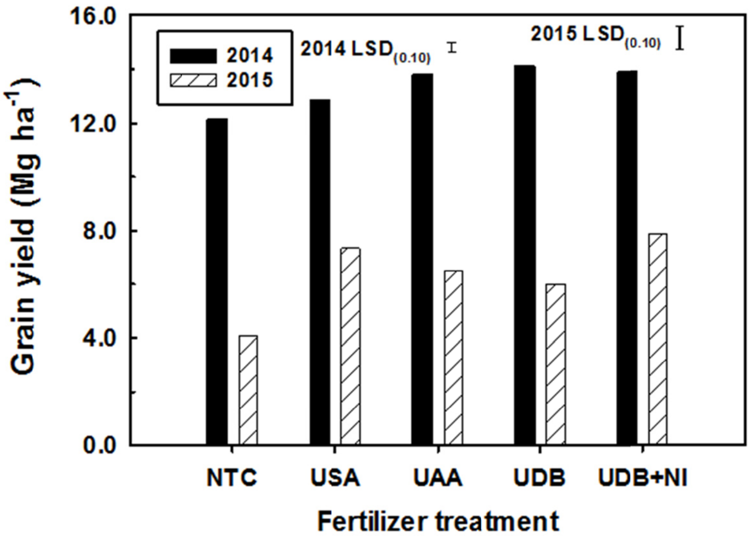

Figure 2. Grain yield response to urea placement and inclusion of a nitrification inhibitor in 2014 and 2015

Note. NTC = non-treated control; USA = urea, surface-applied; UAA = urea incorporated after surface broadcast application; UDB = urea deep banding; UDB + NI = urea deep banding plus nitrification inhibitor. Vertical bar indicate $LSD_{(0.10)}$ values for individual years.

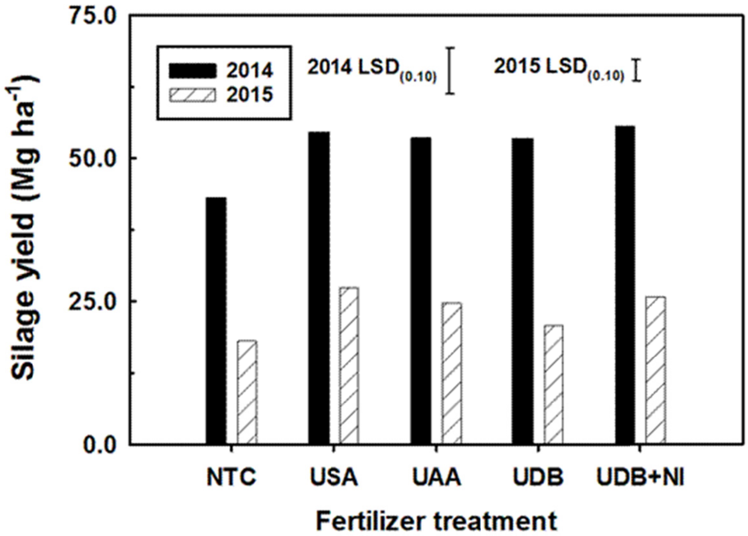

Figure 3. Silage yield response to urea placement and inclusion of a nitrification inhibitor in 2014 and 2015

Note. NTC = non-treated control; USA = urea, surface-applied; UAA = urea incorporated after surface broadcast application; UDB = urea deep banding; UDB + NI = urea deep banding plus nitrification inhibitor. Vertical bar indicate $LSD_{(0.10)}$ values for individual years.

Table 3. Silage tissue N concentration, N uptake and apparent N recovery efficiencies in response to urea placement and inclusion of a nitrification inhibitor in 2014 and 2015

Treatment	Tissue N concentration	Nitrogen Uptake	Apparent N Recovery Efficiency
	--------------- % ---------------	------- kg N ha^{-1} -------	------------------ % -------------------
2014			
NTC†	0.73	177	-
USA	0.96	278	47
UAA	0.92	267	44
UDB	1.03	278	50
UDB+NI	1.21	357	79
$LSD_{(0.10)}$‡	0.20	80	NS
2015			
NTC	0.70	62	-
USA	1.33	167	52
UAA	0.75	102	20
UDB	0.77	75	7
UDB+NI	0.77	80	9
$LSD_{(0.10)}$	NS	83	NS

Note. †NTC = non-treated control; USA = urea, surface-applied; UAA = urea incorporated after surface broadcast application; UDB = urea deep banding; UDB + NI = urea deep banding plus nitrification inhibitor; NS = not significant.

‡Fishers protected least significant difference at $P \leq 0.10$; NS = Not significant.

Mean tissue N concentrations in silage for the 2015 season ranged from 0.70% in the NTC to 1.34% in the USA (Table 3). Mean N concentration for the USA treatment was at least 43% greater than all other treatments; however, all of the means were not significantly different.

The UDB+NI treatment had 31 to 33% higher N uptake than USA and UAA, respectively (Table 3). However, significantly higher N uptake was observed in the USA treatment compared to the UDB and UDB+NI treatments in 2015. In 2014, N uptake ranged from 177 kg N ha^{-1} in the NTC treatment to 357 kg N ha^{-1} in the UDB+NI treatment. Nitrogen uptake values for the USA, UAA, and UDB treatments were 278, 267, and 278 kg N ha^{-1}, respectively. There were no significant differences between either of the deep banded urea treatments. However, the addition of a NI resulted in a 22% increase in N uptake compared to UDB alone.

Nitrogen uptake for each treatment was lower in 2015 compared to 2014 (Table 3). In 2015, N uptake ranged from 62 kg N ha^{-1} in the NTC to 167 kg N ha^{-1} for USA (Table 3). Surface-applying urea (USA) resulted in a 52% increase in N uptake compared to UDB+NI, and a 55% increase in N uptake compared to UDB. No differences in N uptake were observed between the UAA, UDB+NI, UDB, and NTC treatments.

Calculations of apparent N recovery efficiency, which is a measure of N use efficiency, showed no significant differences among the treatments in 2014 and 2015 (Table 3). In 2014, apparent recovery efficiency ranged from 44 to 79% and in 2015 from 7 to 52%. The relatively lower N use efficiency in 2015, especially with the UAA, UDB and UDB+NI treatments is consistent with the lower N uptake observed with those treatments that included deeper fertilizer placement during a year with excessively high precipitation (Figure 1B).

3.4 Grain Moisture and Quality

Corn grain moisture was also significantly different between 2014 and 2015, which could have been due to differences in rainfall distribution and possible N fertilizer effects on plant maturity (Table 4). In 2014, the overall average grain moisture content for the experimental field was 196.6 g kg^{-1}, while in 2015, the average moisture content for the experimental field was 104.6 g kg^{-1}. In 2014, grain from the UAA plots contained the lowest moisture content (192.4 g kg^{-1}), while grain from UDB+NI contained the highest moisture content (200.4 g kg^{-1}) (Table 4). Grain moistures were not significantly different between UDB and UDB+NI plots, but were significantly different from other treatments. The means from the NTC, USA, and UAA were not significantly different from each other.

Table 4. Selected corn grain quality characteristics in response to urea placement and inclusion of a nitrification inhibitor in 2014 and 2015

Treatment	Corn Grain Content			Grain Moisture
	Starch	Protein	Oil	
	g kg^{-1}			
2014				
NTC[†]	738.4	71.4	40.0	195.8
USA	730.4	86.6	39.4	194.0
UAA	727.6	86.6	40.8	192.4
UDB	729.2	88.0	39.2	200.2
UDB+NI	725.8	88.4	40.9	200.4
$LSD_{(0.10)}$	5.4	2.8	NS	3.4
2015				
NTC	745.0	61.2	38.6	90.0
USA	742.0	62.0	39.4	97.2
UAA	743.8	60.2	38.7	102.6
UDB	736.0	64.8	41.4	113.0
UDB+NI	738.8	61.2	41.2	120.4
$LSD_{(0.10)}$[‡]	6.8	NS	2.4	11.4

Note. [†]NTC = non-treated control; USA = urea, surface-applied; UAA = urea incorporated after surface broadcast application; UDB = urea deep banding; UDB + NI = urea deep banding plus nitrification inhibitor.

[‡]Fisher's protected least significant difference at $P \leq 0.10$; NS = not significant.

Grain moisture content in 2015 ranged from 90.0 g kg^{-1}, in the NTC treatment to 120.4 g kg^{-1} in the UDB+NI treatment (Table 4), which was much lower than what was observed in the 2014 season. The grain moisture content resulting from the UDB, USA, and UAA treatments were 113.0, 97.2, and 102.6 g kg^{-1}, respectively. The UDB+NI treatment was not statistically significantly different from the UDB treatment; however, it was greater than the UAA, USA, and NTC.

Treatment and year were significant factors influencing grain starch and protein concentrations over the two growing seasons (Table 4). There also were significant interactions between the two seasons concerning protein concentrations (P = 0.0005). A higher cumulative rainfall amount in 2015 (Figure 1B) can explain the influence year has on grain quality and suggests that N fertilizer placement can react differently depending on the growing season conditions and precipitation. Starch concentrations in corn grain from the 2014 growing season ranged from 725.8 g kg^{-1} in the UDB+NI plots to 738.4 g kg^{-1} in the NTC treatment (Table 4). All treatments were significantly lower than the NTC treatment by at least 10 g kg^{-1}, but were not significantly different from each other. In 2015, mean starch concentrations ranged from 736.0 g kg^{-1} in the UDB treatment to 745.0 g kg^{-1} in the NTC treatment. The UDB, UDB+NI and USA treatments had similar grain starch concentrations. However, there were significant differences between the two years. Mean starch concentrations were greater in 2015 than in 2014.

Protein concentrations in 2014 ranged from 71.4 g kg^{-1} in the NTC to 88.4 g kg^{-1} in the UDB+NI (Table 4). All treatments had protein concentrations that were significantly higher than the NTC treatment, but the fertilizer placement treatments were not significantly different from each other. In 2015, no significant differences among protein concentrations were observed. Oil concentration was similar among treatments in 2014. However, oil concentration was greatest with UDB, UDB+NI, and USA.

4. Discussion

Deep banding N fertilizers with or without a NI has been observed to reduce N loss and increase NUE possibly due to fertilizer placement in closer proximity to roots and reduction in N loss due to runoff and other possible N loss processes. For example, Reeves and Touchton (1986) observed that deep banding N fertilizer with strip tillage produced the highest grain yields compared to surface-applied urea. A similar result of higher corn yields with the combined use of strip tillage and deep banded urea compared to a no-till surface urea application was observed in poorly-drained claypan soils (Nash et al., 2013). These corn grain yield results were similar to the 2014 results found in this study in which the UAA, UDB and UDB+NI fertilizer placement treatments resulted in higher grain yields than that of the USA treatment. In contrast to other studies, the effect of tillage on yield response was not a factor. However, this pattern was not observed in 2015, possibly because of the increased rainfall in the 2015 growing season (124 mm of rainfall more than in 2014) especially in the early part of the growing season. During the 2015 growing season, the USA treatment had higher grain production. These results indicate that the saturated soil conditions in the beginning of the growing season in 2015 may have limited the growth of corn roots with depth so that roots were unable to absorb the deep banded fertilizer N, but were able to obtain the surface and shallow-placed N fertilizer. Under these conditions, the use of an NI was also effective for increasing yields with the deep banded urea fertilizer placement treatment possibly due to reduced nitrate leaching.

Lehrsch et al. (2000) observed at least a 5% increase in corn grain yield from banded N fertilizer compared to that of broadcast fertilizer which was similar to the results in this study. In 2014, the UDB and UDB+NI treatments produced grain yields that were 10% and 8% more than the USA treatment, respectively. In 2015, UDB+NI yielded 7% more than the USA treatment. Furthermore, Randall et al. (2003) observed a 5% increase in grain yield when nitrapyrin was utilized in corn production. These results were also further supported by Mengel et al. (1982) who observed an increase in grain yield when N fertilizer was injected below the soil surface compared to surface applied N sources. Grant et al. (2001) also observed that banding fertilizer increased grain yield. In wheat, Blackshaw et al. (2004) observed a 12% increase when banding ammonium nitrate compared to broadcast ammonium nitrate during spring application. It is possible that in their study, banding N fertilizer reduced N loss by providing more opportunity for N uptake due to the proximity of the fertilizer to the plant roots.

Even though grain yields were higher in 2014, corn population was lower compared to 2015. This result was unexpected since the 2015 growing season was much wetter than in the 2014 growing season. With the wetter spring in 2015, there was a higher probability for poor seed germination and stand establishment, but this result based on final corn plant population was not observed. However, corn plant populations for both 2014 and 2015 were higher than the average population of 56,000 plants ha^{-1}, which North American farmers have utilized to optimize profit (Williams II, 2012).

Multiple factors may affect corn grain moisture content including the time of harvest, climate, the tillage system used, corn hybrid grown, and application of banded starter fertilizer (Vetsch & Randall, 2000; Wolkowski, 2000; Vetsch & Randall, 2002). Effects of starter fertilizer banding placement on lowering corn grain moisture when they occur are often attributed to a more rapid early season corn growth and rate of maturation with banding at planting (Beegle et al., 2007). Greater plant N availability also tends to promote more rapid rates of corn maturation thereby resulting in relative lower grain moisture content. Reduced grain water content is favored by corn growers due to lower costs associated with grain drying (Wolkowski, 2000).

In this research, grain moisture content did not directly relate to N uptake resulting from the N fertilizer treatments and was generally lower with deep banding compared to surface or shallow incorporation. From an economic standpoint, the lower grain moisture in 2015 would have been cheaper to dry for farmers. A possible reason the grain moisture was much lower is because of the interaction of rainfall distribution and the effects of N on corn maturation. The dry conditions experienced in the late summer in 2015 could also have increased the rate of grain drying.

Nitrogen fertilizer placement methods did not consistently affect silage yields and this response appeared to be affected by differences in precipitation during the two years of this research. Lehrsch et al. (2000) observed a 5 to 26% increase in silage yields for banded fertilizer compared to when the N fertilizer was surface broadcast-applied. Their research results may differ from this research because their research was primarily conducted under irrigated and not rain-fed conditions and the soils in this research were poorly-drained. Greater yield response to banded starter fertilizer under irrigated versus rain-fed conditions has also been observed by Wortmann et al. (2006). The difference in silage yields among the two years of this research could be explained by the increased early season and cumulative rainfall amount in the 2015 growing season compared to that of 2014 which favored surface N fertilizer application.

Nitrogen concentration in the corn silage was not affected by treatment or year. In accordance with these results, Nash et al. (2013) compared corn treatments of no-till/surface broadcast N fertilizer versus strip-till/deep banded N fertilizer and observed minimal differences in earleaf N concentrations among these two treatments that differed in both tillage and N fertilizer placement.

In 2014, UDB and UDB+NI increased N uptake and N use efficiency. This was similar to the results of Lehrsch et al. (2000) in which they observed a 6% increase in N uptake in banded treatments compared to surface broadcasted treatments. Takahashi et al. (1991) reported that deep placed N fertilizer increased NUE by 22% compared to top-dress applied N in fields grown under soybean. These studies suggested that combining multiple management practices can increase NUE. The 2015 results did not follow the same pattern as 2014. In 2015, the USA treatment produced the highest NUE compared to UDB and UDB+NI. The 2015 results were opposite of the findings of Moraghan et al. (1984), who observed greater plant N amounts (4%) for banded urea compared to surface-applied or incorporated urea. In their study, sorghum treated with banded urea was efficient in recovering N almost 18% more than sorghum treated with surface-applied or incorporated urea. These observations could explain why they observed an increase in grain yield production, which was similar to the 2014 results in this study. The difference in response among the two years for the study could have occurred because this study was performed on poorly-drained claypan soils, which are susceptible to gaseous N loss (Nash et al., 2012). This explanation can further be supported by the fact that cumulative rainfall during 2015 was greater and more intense early in the growing season which may have inhibited deep root growth as compared to the conditions experienced in 2014.

The addition of a NI to deep banded urea resulted in a 23% increase in N uptake in 2014 and a 6% increase in 2015. These findings are similar to that of Randall et al. (2003) in which they observed a 23% increase in N uptake in corn with the addition of nitrapyrin to anhydrous ammonia. Even though their study was conducted in the autumn months, these results were similar to this study in which fertilizer was applied prior to planting. In 2015, there was also a significant increase (52%) in N uptake in the USA treatment compared to UDB and UDB+NI. Higher cumulative rainfall during the 2015 growing season could have made deep banding N treatments less effective due to poor early root growth and development. Practicing multiple management practices including applying deep banded urea with a NI has the ability to provide many benefits to crop production including an increase in N uptake and NUE.

Some variability in NUE values were observed in 2014 and a high NUE was observed in 2014 for UDB+NI. In general, NUE was highest for the UDB+NI treatment in 2014 and for the USA treatment in 2015 illustrating the interactive effect of climatic conditions on response to N fertilizer placement.

The higher NUE in 2014 provides an explanation for the higher grain protein concentrations in 2014 because protein content is increased by N application when N is not the most limiting factor of growth (Gauer et al., 1992). This is further supported by decreased NUE in 2015. Treatments did not influence corn grain oil content in 2014, but were a significant factor in 2015. The 2014 results are similar to Miao et al. (2006), in which they observed that N fertilization did not heavily influence grain oil content. Corn grain oil results in 2015 could have been influenced by increased precipitation, environmental N loss, and decreased NUE. However, these results suggest there are other factors not observed in this study influencing oil concentration.

5. Conclusions

These results indicate that the effectiveness of different N fertilizer placement strategies for corn production in a poorly-drained claypan soil was influenced by climatic conditions. Deep-banding urea fertilizer was more effective in a relatively-well distributed high rainfall year, but a surface urea application increased corn grain yields and N uptake in a high rainfall year which had excessive precipitation early in the growing season. We speculate that this difference in response was due to the effects of excessive early season rainfall on inhibiting root growth deeper into the soil. Deep-banded urea with a NI may further benefit crop production due to the delay in nitrification. Results of this study suggest that combining multiple management practices in poorly-drained claypan soils, such as deep banding and use of a NI, could increase crop production under certain climatic conditions. In areas where high cumulative rainfall limits root growth, deep banding N fertilizer may not be as effective and, if deep banding is utilized, addition of a NI with the deep banded fertilizer may be an important safeguard to limit corn yield losses.

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