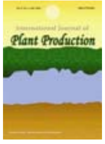

International Journal of Plant Production 7 (3), July 2013
ISSN: 1735-6814 (Print), 1735-8043 (Online)
www.ijpp.info

GUASNR

Corn yield response to polymer and non-coated urea placement and timings

P.R. Nash[a], K.A. Nelson[b,*], P.P. Motavalli[a]

[a]*Dept. of Soil, Environmental and Atmospheric Sciences, Univ. of Missouri, Columbia, MO 65211.*
[b]*Div. of Plant Sciences, Univ. of Missouri, Novelty, MO 63460.*
*Corresponding author. E-mail: nelsonke@missouri.edu

Received 28 January 2012; Accepted after revision 14 February 2013; Published online 1 April 2013

Abstract

Poorly drained claypan soils can increase the importance of tillage and N management for corn (*Zea mays* L.) production. Field research in 2008, 2009 and 2010 (high rainfall years) near Novelty, MO (40° 1' N, 92° 11' W) sought to determine the effect of polymer-coated urea (PCU) placement [strip-tillage (ST) deep banded and no-till (NT) broadcast] and application timing (fall, early preplant and preplant) on red clover (*Trifolium pratense* L.) biomass and corn response compared to non-coated urea (NCU) and anhydrous ammonia (AA) in the presence and absence of nitrapyrin a nitrification inhibitor. Strip-tillage reduced clover dry weights 20% in 2008 and 2009 and early preplant ST reduced dry weights 40 to 45% in 2010 compared to NT. Corn plant population was 8,100 to 8,400 plants ha^{-1} greater with ST compared to NT. Preplant applications of AA plus nitrapyrin, AA, ST placement of PCU and NCU increased grain yields 1 to 1.2 Mg ha^{-1} compared to fall applications of these fertilizer sources. Fall and preplant ST placement of PCU increased grain yields 1.2 Mg ha^{-1} compared to NCU. Strip-till placement of PCU and NCU increased yields 2.1 to 3.2 Mg ha^{-1} over broadcast applications of these fertilizer sources. Strip-till placement of PCU synergistically increased yield over NCU and broadcast applications of PCU or NCU due to increased stands and possibly due to better plant utilization of the banded N fertilizer utility.

Keywords: Controlled-release fertilizer; Cover crop; Enhanced efficiency fertilizer; No-till; Strip-tillage.

Introduction

The central claypan region's 4 million ha of soil includes part of North central Missouri, Southern Illinois and Southeast Kansas. Claypan soils contain a subsoil layer 20 to 40 cm below the surface with at least 100% higher clay content than the overlying horizon (Jung et al., 2006; Myers et al., 2007). The claypan layer's poor internal drainage can prove a challenge to agricultural practice. The poor drainage of rain results in saturated soils that can affect management decisions and reduce grain yields (Nelson et al., 2009b).

In corn, nitrogen recovery efficiency may be increased management practices that minimize N loss and maximize plant uptake. Agricultural producers can profit from improved N management systems by increasing yields and/or lowering N fertilizer requirements by increasing N recovery efficiency. Farmers may have limited time to apply N fertilizers at spring planting for several reasons: high work load, large production area and wet fields. Such conditions sometimes require producers to apply N before planting (Scharf et al., 2002). In these situations, some farmers apply N in fall on a portion of their fields to reduce time conflicts in spring. Others apply N to all of their fields in fall because lower fertilizer costs can negate the lower yields and returns associated with applying N in fall. In Minnesota, a single fall application of N fertilizers did not promote efficient N management and high yields because the lag time between application and plant uptake increased N loss (Randall et al., 2003). The use of the nitrification inhibitor, nitrapyrin (2-chloro-6-(trichloromethyl) pyridine), with anhydrous ammonia applied in the fall to a heavy clay soil with tile drainage reduced drainage loss of nitrate by 10% compared to fall applications of anhydrous ammonia without nitrapyrin (Randall and Vetsch, 2005). In Missouri's claypan region, farmers commonly use anhydrous ammonia as an N source for corn production. However, anhydrous ammonia requires specialized equipment for storage, handling and application, which causes many producers to choose other N fertilizers.

Urea-based fertilizers are the world's most popular N sources, accounting for 43% of global N fertilizer sales (Bouwman et al., 2002). Urea is highly soluble and has a large potential for N loss through leaching in sandy soils (Wilson et al., 2009) or sub-surface tile drainage in poorly drained soils (Drury et al., 2009). Lateral transport of urea-derived N in poorly drained soils, without tile drainage, may be an important loss mechanism. Research in a claypan soils has found minimal lateral transport and leaching loss of N from urea, while gaseous emissions accounted for approximately 35% of N fertilizer loss (Blevins et al., 1996).

Farmers sometimes like no-till systems more than conventional tillage because of their higher yield potential (Al-Kaisi and Licht, 2004; Al-Kaisi and Kwaw-Mensah, 2007; Mehdi et al., 1999; Torbert et al., 2001) that comes from improved soil conservation, soil fertility and lower production time and costs (Lithourgidis et al., 2005). However, no-till's yield benefits depend on differences in environmental conditions and management practices including variation in soil type, seedbed conditions, climate, N application timing, placement, N fertilizer source and seasonal weather that affect production (Mehdi et al., 1999; Hendrix et al., 2004; Licht and Al-Kaisi, 2005a). No-till has been reported to reduce yields in some situations. Nitrogen applied to the soil surface with no-till systems is more likely to be lost from runoff and gaseous losses. This results in lower yield production (400 kg ha^{-1}) than conventional tillage compared to N placed 15 to 20 cm deep in the soil (Riedell et al., 2000). Compared to conventional tillage systems, no-till systems have a higher potential for reduced plant emergence (Hendrix et al., 2004; Licht and Al-Kaisi, 2005; Lithourgidis et al., 2005), slower spring growth and development and delayed tasseling (Licht and Al-Kaisi, 2005b; Halvorson et al., 2006). These characteristics, which are associated with increased bulk density, moisture content and lower soil temperature in the spring due to greater cover of surface residues (Mehdi et al., 1999), may contribute to lower yields compared to conventional tillage (Vetsch and Randall, 2004; Halvorson et al., 2006). Problems with plant emergence, delayed plant growth and high potential N loss with surface or fall application of N may increase with poorly drained claypan soils during abnormally dry or wet growing seasons. Alternative management options to minimize problems and increase corn yields include using winter legume cover crops, minimal tillage and enhanced N-use efficiency forms of urea fertilizer.

Crop rotations that include winter legume cover crops interseeded into a prior crop, such as wheat or planted after fall harvest may increase soil fertility and reduce N requirements, while sustaining high crop yields the following year. Adopting interseeded cover crops, such as red clover (*Trifolium pratense* L.), in crop rotations has potential to sustain high crop yields and possibly reduce fertilizer N requirements. Frost interseeding of clover into wheat was a common practice in the claypan region when more of the area was cropped to wheat. In Canada, employing strip-tillage after interseeded clover increased yields 36% compared to planting no-till into red clover (Drury et al., 2003). Studies incorporating red clover into crop rotations have shown mixed results for the clover's ability to increase soil N and grain yields. Averaged over a 5-year field study, incorporating wheat and red clover residue into a corn-soybean rotation increased corn grain yields 4% with ridge tillage and 6% with moldboard plow tillage (Katsvairo and Cox, 2000). It was not clear whether yield increases came from increased soil N levels through fixation or improved soil properties. Vyn et al. (2000) reported that red clover supplied 70% more organic N than winter rye (*Secale cereale* L.) and resulted in 2.16 to 3.34 Mg ha^{-1} greater corn grain yields when fertilizer N was not applied. Another study found inconsistencies in red clover's ability to increase soil N; however, corn yields increased from red clover's non-N related benefits, such as reduced disease and insect incidence with rotation, increased water infiltration and moisture conservation (Henry et al., 2010).

Strip-till (ST) is a new alternative minimal tillage practice that allows for deep banded placement of dry, liquid or gas-based N fertilizers within narrow tilled planted rows without requiring tillage of the entire field. Because only the corn rows are tilled, this method not only fosters many of the soil conservation and fertility benefits associated with no-till but also lowers the potential for N loss through its deep band placement. Other benefits accrue from tilling the soil in the seeded row. The approach breaks up soil aggregates and incorporates surface residues that lower bulk density. It increases drainage and drying within the seedbed and ultimately allows soils to warm earlier in spring, which increases plant emergence and growth (Randall and Hill, 2000). Previous studies concluded that strip-till produced yields similar to no-till (Vetsch and Randall, 2004; Al-Kaisi and Licht, 2004; Al-Kaisi and Kwaw-Mensah, 2007), but that strip-tillage increased yields 1.9 Mg ha^{-1} when corn was planted into clover residue (Drury et al., 2003).

Recently, polymer-coated urea fertilizer (PCU) has been sold for use in agronomic crops to control N release from urea into the soil over time (Wilson et al., 2009). Making urea available for microbial N transformations slowly after application may reduce potential ammonia volatilization and N leaching losses compared to traditional dry urea fertilizer (Blaylock et al., 2004; Blaylock et al., 2005; Motavalli et al., 2008). PCU's mode of action differs from nitrification inhibitor products, such as nitrapyrin, which lower N loss by restricting microbial activity involved with nitrification (Walters and Malzer, 1990). Rochette et al. (2009b) reported that surface applications of Environmental Smart Nitrogen (ESN), a PCU fertilizer for agronomic crops, resulted in 60% reduction in ammonia volatilization loss as compared to conventional dry urea fertilizer (NCU). Grain-yield benefits from PCU applications depend on several factors, including weather, climate, soil properties, landscape position, soil moisture, management systems and the polymer-coat's thickness and integrity. Research has shown that PCU applications increased grain yields more than NCU in corn (Blaylock et al., 2004; Blaylock et al., 2005) and potatoes (Zvomuya et al., 2003). Corn grain yields on a claypan soil in Northeast Missouri increased by 1530 to 1810 kg ha^{-1} in poorly drained, low-lying areas when PCU was applied compared to NCU (Nelson et al., 2009; Noellsch et al., 2009). However, yields were similar or lower than with NCU fertilizer during a drier growing season and at side slope and summit landscape positions (Noellsch et al., 2009).

Nitrogen, tillage and water management are important factors in corn production. However, properties of claypan soils increase the impact of management decisions for no-till corn farmers due to a greater potential for gaseous N loss and challenging seedbed conditions. Minimal tillage practices, such as strip-tillage, may greatly benefit production in the region, but agronomic research on this tillage practice in conjunction with use of enhanced efficiency fertilizers is limited. Integrating enhanced efficiency fertilizers and conservation strip-tillage systems may help farmers manage high-residue systems under no-till that use surface fertilizer applications. In addition, strip-till placement of PCU may allow farmers the option of applying fertilizer in the fall rather than anhydrous ammonia. The objective of this research was to determine the effect of PCU placement (strip-till and no-till, broadcast) and application timing (fall, early preplant and preplant) on clover biomass and corn response compared to NCU and anhydrous ammonia in the presence or absence of a nitrification inhibitor.

Materials and Methods

This study was conducted from 2008 to 2010 at the University of Missouri's Greenley Memorial Research Center (40° 1' 17" N 92° 11' 24.9" W) near Novelty, MO on a Putnam silt loam (fine, smectitic, mesic, Vertic Albaqualfs). Soil properties (Table 1) were analyzed from bulk density cores taken from a single depth (0-10 cm) in 2008 and at two depths (0-10 and 10-20 cm) in 2009 and 2010. Depth to the claypan at this research station ranged from 46 to 60 cm (data not presented).

Table 1. Soil properties in 2008, 2009 and 2010.

Year	Depth	Bulk Density	pH (0.01 M $CaCl_2$)	Organic matter	Neutralizable acidity	Cation exchange capacity	Bray I P	Exchangeable (1M NH_4AO_c) Ca	K	Mg	NO_3-N
	cm	g cm^3		g kg^{-1}	$cmol_c$ kg^{-1}		mg kg^{-1}	kg ha^{-1}			kg ha^{-1}
2008[†]	0-10	-----	6.8	26	0.17	15.9	15.3	5990	345	538	-----
2009	0-10	1.32	6.5	28	1.00	14.9	29.3	5333	380	428	1.8
	10-20	1.38	6.0	23	3.17	17.6	9.3	5414	239	514	2.0
2010	0-10	1.38	6.7	32	0.63	14.9	35.4	5490	368	421	0.8
	10-20	1.47	6.5	23	1.13	15.2	8.8	5432	197	453	0.0

[†] Bulk density, soil nitrate concentration and soil samples taken at a depth of 10-20 cm were not determined in 2008.

The experiment was arranged in a split-plot design with three replications in 2008 and 2009 and four replications in 2010. Plots of 3 by 21 m were used on different fields each year. The main plot was N fertilizer application timing (fall, early preplant and preplant). Sub-plots were N fertilizer sources and fertilizer placement [PCU (ESN, Agrium Advanced Technology, Denver, CO) strip-till deep-banded or broadcast, NCU strip-till deep-banded or broadcast, anhydrous ammonia in the presence and absence of nitrapyrin (N-Serve, Dow Agro Sciences, Indianapolis, IN) at 560 g ai ha^{-1} and a non-treated control with strip-tillage and no-till. Fertilized treatments were applied at 140 kg N ha^{-1} to detect differences among enhanced-efficiency fertilizers. The broadcast N applications were no-till seeded and fertilizer was applied with a hand spreader. Strip-tillage (30.5 cm width, 20 cm depth and 76.2 cm spacing) was conducted with a 2984 Maverick unit (Yetter Manufacturing, Inc., Colchester, IL). Nitrogen fertilizers were banded to a depth of 15 cm below the planted row and fertilizer was delivered using a Gandy Orbit-Air (Gandy Company, Owatonna, MN) ground-driven metering system.

'DK 61-69 VT3' was planted (John Deere 7000, Deere and Co., Moline, IL) in 76 cm rows at 74,130 seeds ha^{-1}. The planter was equipped with Shark-tooth® residue cleaners (Yetter Manufacturing, Inc., Colchester, IL) used in tandem with a no-till coulter. The residue cleaners performed well in heavy residue of the no-till plots and provided a smooth seedbed above in strip-tilled plots (visual observation). Red clover was frost interseeded at 9 kg ha^{-1} into wheat (*Triticum aestivum L.*) the year prior to each experiment. Planting and harvest dates, crop protection chemicals and fertilizer application dates are reported in Table 2. Weather data collected on site at the Greenley Memorial Research Center weather station included daily rainfall, air temperature and soil temperature at a depth of 5 cm (Figure 1).

Red clover was 15 to 20 cm tall at the time of the burn down herbicide application (Table 2). In order to evaluate differences in plant residue among fertilizer sources and placement, aboveground biomass was collected from two 30 by 76 cm quadrats prior to the burn down herbicide application from each plot for the fall and early preplant treatments, oven dried at 65 ^{o}C, and weighed. Corn heights in mid-June, chlorophyll meter readings (SPAD units) between the VT to and R2 growth stage (Ritchie et al., 1993) and harvested plant population were determined. A small-plot combine (Wintersteiger Delta, Salt Lake City, UT) was used to harvest and weigh the centermost two rows of each plot. Seed moisture was determined at harvest and yield adjusted to 150 g kg^{-1} prior to data analyses. Grain samples were collected from each plot and ten subsamples analyzed for oil, protein and starch with a Foss Infratec 1241 (Eden Prairie, MN) near infrared spectrometer using previously established calibrations (Paulsen et al., 2003; Paulsen and Singh, 2004; Singh et al., 2005) similar to previous research (Nelson et al., 2009; Nelson and Meinhardt, 2011). All data were subjected to ANOVA using PROC GLM (SAS, 2010) and combined over main effects and/or years in the absence of significant interactions. Means were separated using Fisher's Protected LSD at P=0.05.

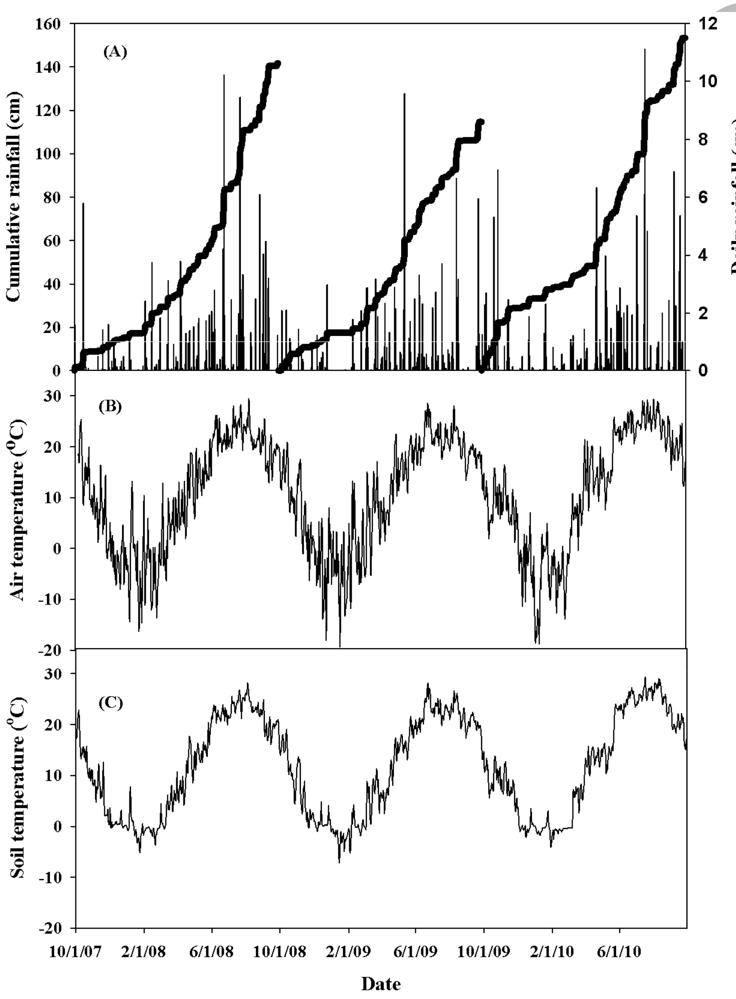

Figure 1. Daily (bars) and cumulative rainfall (lines) (A), daily average air temperature (B), and soil temperature (^{o}C) at 5 cm depth with soybean residue from fall 2007 to 2010.

Table 2. Planting, N application, crop protection chemical application and harvest dates in 2008, 2009 and 2010.

Year	Crop management[†]	Date
2008	Planting date	6 May
	N applications timings	
	Fall	11 Nov.
	Early preplant	7 Apr.
	Preplant	5 May
	Burndown	
	Glyphosate at 1.06 kg ae ha^{-1}	28 Apr.
	2,4-D amine at 1.05 kg ai ha^{-1}	28 Apr.
	Preemergence herbicide	
	Acetochlor at 1.9 kg ai ha^{-1}	16 May
	Atrazine at 0.94 kg ai ha^{-1}	16 May
	Glyphosate at 1.06 kg ae ha^{-1}	16 May
	Harvest date	4 Oct.
2009	Planting date	23 Apr.
	N applications timings	
	Fall	3 Nov.
	Early preplant	4 Apr.
	Preplant	23 Apr.
	Burndown	
	Glyphosate at 1.06 kg ae ha^{-1}	28 Apr.
	Dicamba at 0.28 kg ai ha^{-1}	28 Apr.
	Preemergence herbicide	
	S-metolachlor at 2.25 kg ai ha^{-1}	4 May
	Atrazine at 0.84 kg ai ha^{-1}	4 May
	Glyphosate at 1.06 kg ae ha^{-1}	
	Harvest date	19 Oct.
2010	Planting date	14 Apr.
	N applications timings	
	Fall	6 Nov.
	Early preplant	1 Apr.
	Preplant	14 Apr.
	Burndown	
	S-metolachlor at 2.25 kg ai ha^{-1}	16 Apr.
	Atrazine at 0.84 kg ai ha^{-1}	16 Apr.
	Mesotrione at 0.23 kg ai ha^{-1}	16 Apr.
	Dicamba at 0.56 kg ai ha^{-1}	16 Apr.
	Lambda-cyhalothrin at 0.02 kg ai ha^{-1}	16 Apr.
	Postemergence	
	Glyphosate at 1.06 kg ae ha^{-1}	22 June
	Harvest date	28 Sept.

[†] 2,4-D amine, 2,4-D-Dichlorophenoxyacetic acid; Acetochlor, 2-chloro-N-(ethoxymethyl)-N-(2-ethyl-6-methylphenyl) acetamide; atrazine, 6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine; dicamba, 3,6-dichloro-o-anisic acid; glyphosate, *N*-(phosphonomethyl) glycine; lambda-cyhalothrin, [1a(*S**),3a(Z)]-(±)-cyano-(3-phenoxyphenyl) methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate; mesotrione, 2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione; and *S*-metolachlor, 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide.

Results and Discussion

From 2000 to 2007, growing season conditions averaged 59 cm for rainfall, 20.0 °C for air temperature and 20.2 °C for soil temperature at 5 cm depth (data not presented). During the 2008 and 2009 growing seasons, average air and soil temperatures were approximately 1 to 1.6 °C lower than the prior eight-year average and the 2010 growing season was approximately 0.7 to 1 °C higher. Total rainfall during the study was 36 to 85% higher than the prior eight-year average at 107 cm in 2008, 80 cm in 2009 and 108 cm in 2010 (Figure 1). Rainfall during growing seasons was similar and evenly distributed throughout the study, with majority of rainfall occurring between Apr. and July. However, fall was abnormally wet during the 2009-2010 season.

In 2008 and 2009, fertilizer source and placement affected clover biomass (Table 3), but application timing (fall or early preplant) did not affect (P=0.59) clover dry weights (data not presented). Clover dry weights (2.2 to 2.5 g m^{-2}) were similar among strip-till treatments and anhydrous ammonia plus nitrapyrin. There was no difference in clover dry weights between anhydrous ammonia applied alone or with nitrapyrin. Strip-tillage reduced clover dry weights 20 to 21% regardless of the fertilizer source. This reduction was probably due primarily to tillage, which represented about 40% of the area affected by this treatment. In 2010, a two-way interaction (fertilizer source/placement*application timing) existed that was probably related to excessive fall and winter rains (Figure 1) and allowed additional growth and access to the applied fertilizer. Unlike 2008 and 2009, all but one fall N treatments increased clover dry weights compared to the broadcast non-treated control. The exception was broadcast PCU and anhydrous ammonia in the presence and absence of nitrapyrin (Table 3). Fall strip-tillage with PCU or NCU increased clover dry weights 1.9 and 1.4 g m^{-2} compared to a broadcast application of these fertilizer sources. Dry weights were 63% greater than an early preplant strip-tillage application. An early preplant strip-tillage application of PCU or NCU reduced clover dry weights 40 to 45% compared to a broadcast surface application. An early preplant application of anhydrous ammonia increased dry weight 1.9 g m^{-2} more than anhydrous ammonia plus nitrapyrin. This indicated clover's increased N uptake from this fertilizer application.

Fertilizer application timing had no effect (P=0.30) on harvested plant population (Table 4), but plant population increased with strip-tillage plus NCU (8,100 plants ha^{-1}) or PCU (8,400 plants ha^{-1}) compared to no-till broadcast placement (Table 5). These results were similar to a study conducted on a silt loam soil where plant populations with no-till were 37% lower than with strip-till, which may have reflected higher soil moisture and cooler soils in the planted row of no-till compared to strip-till (Hendrix et al., 2004). Strip-till with deep-banded N fertilizer maintained high plant populations over moderately wet to very wet growing conditions. Studies have reported that tilled plant rows improved seedbed conditions more than no-till, which may explain why strip-till treatments in our study maintained high plant populations in poor growing conditions (Randall and Hill, 2000).

Table 3. Nitrogen fertilizer source (140 kg N ha^{-1}) and placement main effect on clover dry weights in 2008 and 2009 and the interaction between fertilizer source, placement and application timing in 2010 on clover dry weights prior to burn down herbicide application.

Fertilizer and placement	2008 and 2009[†]	2010	
		Fall	Early preplant
		g m^{-2}	
Anhydrous ammonia	2.8	4.0	4.1
Anhydrous ammonia + nitrapyrin[‡]	2.5	4.8	2.2
Strip-till polymer-coated urea[§]	2.2	6.3	2.3
Strip-till non-coated urea	2.4	6.2	2.3
Strip-till non-treated control	2.2	5.4	2.7
Broadcast polymer-coated urea	2.8	4.4	4.0
Broadcast non-coated urea	3.0	5.8	4.2
Broadcast non-treated control	2.8	3.6	3.5
LSD (P=0.05)	0.5	1.4	

[†] Data were combined over years (2008 and 2009) and application timing (fall, early preplant and preplant).
[‡] Nitrapyrin was applied at 560 g ai ha^{-1}.
[§] Polymer-coated urea (ESN, Agrium AT, Inc, Calgary, Canada).

Table 4. Corn plant population and height in early June. Data were combined over fertilizer source/placement and year.

Application timing	Population	Height
	No. ha^{-1}	cm
Fall	54,300	67
Early preplant	58,300	73
Preplant	55,300	74
LSD (P=0.05)	NS	5
P-value	0.30	0.01

Table 5. Corn plant population, height in early June each year (2008, 2009 and 2010) and chlorophyll meter readings for different fertilizer sources at 140 kg N ha^{-1}, placements and application timings. Nitrogen was applied at 140 kg N ha^{-1}.

Fertilizer source and placement	Population[†]	Height (early-to mid-June)[‡]			Chlorophyll meter (SPAD VT-R2)[§]		
		2008	2009	2010	Fall	Early preplant	Preplant
	No. ha^{-1}		cm				
Anhydrous ammonia	55,800	60	61	102	46.2	50.1	50.0
Anhydrous ammonia + nitrapyrin[¶]	58,500	57	66	102	50.2	50.0	50.2
Strip-till polymer-coated urea[¶]	60,000	55	72	97	47.1	49.3	48.4
Strip-till non-coated urea	59,000	54	67	95	46.7	49.7	48.9
Strip-till non-treated control	57,800	52	57	78	36.1	31.5	33.0
Broadcast polymer-coated urea	51,600	57	67	84	39.1	44.8	45.7
Broadcast non-coated urea	50,900	56	54	82	38.2	44.9	40.4
Broadcast non-treated control	54,300	51	54	75	36.7	37.1	35.8
LSD (P=0.05)	5,400		7			3.7	

[†] Data were combined over years (2008, 2009 and 2010) and application timing (fall, early preplant and preplant).

[‡] Data were combined over application timing (fall, early preplant and preplant).

[§] Data were combined over years (2008, 2009 and 2010).

Nitrapyrin was applied at 560 g ai ha^{-1}. Polymer-coated urea (ESN, Agrium AT, Inc, Calgary, Canada).

Corn plant heights in early June were slightly taller with early-preplant and preplant N applications compared to a fall N application (Table 4). There was a year*fertilizer source/placement interaction with taller plants in 2010, compared to 2008 and 2009 (Table 5). In 2008, plants were 8 to 9 cm taller with anhydrous ammonia compared to the strip-till and broadcast non-treated control. In 2009, anhydrous ammonia plus nitrapyrin increased plant height 9 cm more than strip-till non-treated control. In 2009 and 2010, broadcast and strip-till placement of PCU produced taller plants than the non-treated controls and in 2009 the plants were taller than with broadcast NCU. In 2010, heights were greatest with anhydrous ammonia in the presence and absence of nitrapyrin. That year, strip-till placement of PCU or

NCU increased plant height 13 cm compared to broadcast applications. These findings support studies reporting delayed plant growth with no-till compared to tillage (Halvorson et al., 2006).

Chlorophyll meter readings from VT-R2 indicated that plants were greener with fall-applied anhydrous ammonia plus nitrapyrin compared to anhydrous ammonia alone (Table 5). This suggest higher N concentrations existed in those plants during those growth stages. Anhydrous ammonia plus nitrapyrin chlorophyll meter readings were similar to strip-till PCU and NCU regardless of the application timing. Fall, early-preplant and preplant strip-till placement of PCU and NCU was greener than a broadcast application of PCU or NCU. The exception was that strip-till PCU was similar to broadcast PCU when applied preplant. Fall-applied broadcast PCU and NCU was not greener than the broadcast non-treated control. Previous research indicated that deep placement of N in bands lowered the rate of microbial N transformations over surface application. This may account for lower volatilization and denitrification N loss (Sommer et al., 2004; Drury et al., 2006; Rochette et al., 2009a, Rochette et al., 2009b; Grant et al., 2010) and contribute to greener plants.

Preplant applications of anhydrous ammonia plus nitrapyrin, anhydrous ammonia, strip-till placement of PCU and strip-till placement of NCU increased grain yields 1 to 1.2 Mg ha^{-1} compared to fall applications of these fertilizer sources (Figure 2). Strip-till placement of PCU had grain yields similar to anhydrous ammonia. This finding was similar to previous research with PCU and anhydrous ammonia in medium-and high-yield environments (Nelson et al., 2009). Anhydrous ammonia plus nitrapyrin had grain yields similar to anhydrous ammonia alone at all three application timings. In three wet years (Figure 1), fall and preplant strip-till placement of PCU increased grain yields 1.2 Mg ha^{-1} compared to NCU, but no difference in grain yields were detected when fertilizers were applied early preplant. This was similar to previous research conducted in Missouri in which corn grain yields increased by 1.5 to 1.8 Mg ha^{-1} in poorly drained, low-lying areas when PCU was applied compared to NCU (Nelson et al., 2009; Noellsch et al., 2009). Strip-till placement of PCU and NCU increased yields 2.1 to 3.2 Mg ha^{-1} over broadcast applications of these fertilizer sources. However, yields for the strip-till non-treated control were similar to no-till non-treated controls regardless of the application timing. This was similar to research on a clay loam soil where grain yields were 1.9 Mg ha^{-1} greater with strip-tillage compared to no-till corn seeded into red clover residue (Drury et al., 2003). However, research conducted using soil with moderate to good drainage found strip-till had yields similar to no-till (Vetsch and Randall, 2004). In that case, yield potential benefits from strip-tillage increased for poorly drained soils. Increased yields may have been due to reduced N loss with deep placement of N compared to surface broadcasting (Grant et al., 2010). This research indicated a stand reduction in no-till compared to strip-till. This finding was similar to research in which yield differences between no-till and strip-till management practices depended largely on differences in plant population. This is because strip-till, deep banding had greater yields in a season where plant population was lower in no-till and surface broadcasted treatment (Hendrix et al., 2004).

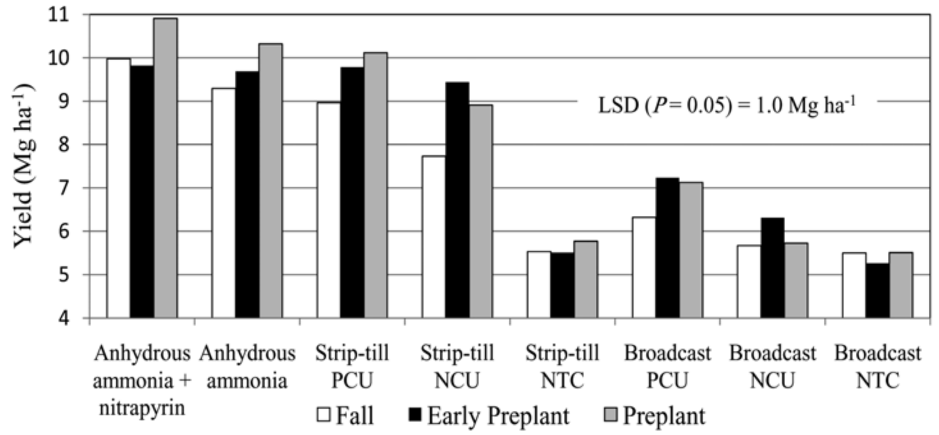

Figure 2. Corn grain yield response to fall, early preplant and preplant applications of polymer-coated urea (PCU was ESN, Agrium AT, Inc, Calgary, Canada), non-coated urea (NCU), or anhydrous ammonia in the presence and absence of nitrapyrin at 560 g ai ha^{-1}. Nitrogen was applied at 140 kg N ha^{-1} except in the non-treated controls (NTC). Data were combined over years (2008, 2009 and 2010) in the absence of a significant (P=0.24) year*application timing*fertilizer source interaction.

Grain moisture (Table 4) and oil (P=0.57, data not presented) concentration were not affected by N fertilizer application timing and neither was grain oil concentration affected by N fertilizer source or placement (P=0.71, data not presented). Grain moisture at harvest was greatest in 2009 followed by 2010 and 2008 (Table 6). Grain moisture was similar among fertilizer sources and placements in 2008. However, anhydrous ammonia plus nitrapyrin and strip-till placement of PCU and

NCU had the lowest grain moisture at harvest in 2009 and 2010. Broadcast PCU and NCU had grain moisture that was 20 to 38 g kg^{-1} greater than strip-till placement of these fertilizers in 2009 and 2010.

Table 6. Grain moisture, protein and starch concentration for different N fertilizer sources (140 kg N ha^{-1}) and placements in 2008, 2009 and 2010.

Fertilizer source and placement	Moisture[†]			Protein			Starch		
	2008	2009	2010	2008	2009	2010	2008	2009	2010
					g kg^{-1}				
Anhydrous ammonia	152	243	172	83	81	76	682	718	722
Anhydrous ammonia + nitrapyrin[‡]	147	235	170	85	81	78	682	721	723
Strip-till polymer-coated urea[§]	150	228	167	82	77	74	681	721	722
Strip-till non-coated urea	151	227	169	82	72	76	681	722	721
Strip-till non-treated control	148	258	182	58	61	75	694	722	723
Broadcast polymer-coated urea	148	255	187	67	73	75	691	722	719
Broadcast non-coated urea	145	265	181	67	68	78	690	721	720
Broadcast non-treated control	149	268	183	62	64	76	694	725	717
LSD (P=0.05)		14			5			6	

[†] Data were combined over application timing (fall, early preplant and preplant).

[‡] Nitrapyrin was applied at 560 g ai ha^{-1}.

[§] Polymer-coated urea (ESN, Agrium AT, Inc, Calgary, Canada).

Grain protein and starch concentrations varied by year (Tables 6 and 7). However, in 2010, there was no difference in grain protein concentration among fertilizer source or placement (Table 6). In 2008 and 2009, grain protein was similar for anhydrous ammonia, anhydrous ammonia plus nitrapyrin and PCU strip-till. In 2008, PCU and NCU strip-till applied had protein concentrations greater than broadcast no-till application. Protein concentration was similar between PCU and NCU regardless of their placement. Starch concentration was 8 to 13 g kg^{-1} greater in the non-treated controls and broadcast applications of PCU and NCU compared to strip-till application of PCU and NCU and anhydrous ammonia in the presence and absence of nitrapyrin. All N source/placements had starch concentrations similar to the broadcast non-treated control except anhydrous ammonia applied alone. There were no differences among fertilizer source/placements in 2010. In 2008 and 2009, grain protein concentration increased as N was applied in fall, early preplant and preplant (Table 7), but in 2010 protein concentration was 7 g kg^{-1} greater when N was applied in fall applied compared to early preplant and preplant. Starch concentration was greater in 2009 and 2010 compared to 2008. There was no difference among application timings in 2008 and 2009, but early preplant and preplant applications increased starch concentration 4 to 6 g kg^{-1} compared a fall application.

Table 7. Grain protein and starch concentration in 2008, 2009 and 2010. Data were averaged over fertilizer sources and placement.

Application timing	Protein			Starch		
	2008	2009	2010	2008	2009	2010
	g kg^{-1}					
Fall	71	69	81	688	723	717
Early preplant	74	72	74	687	720	723
Preplant	75	75	74	686	721	721
LSD (P=0.05)		4			3	

Conclusions

Choosing appropriate tillage and N management practices can be challenging when growing corn using a high-residue clover cover crop system in poorly drained claypan soils. During three wet growing seasons, conditions in these soils were potentially conducive to gaseous N loss and poor plant establishment, which may accounted for lowered grain yield potential of no-till compared to strip-tillage. Grain yields generally increased as N was applied preplant compared to a fall application, except for broadcast NCU. Preplant applications of anhydrous ammonia plus nitrapyrin, anhydrous ammonia, strip-till placement of PCU and strip-till placement of NCU increased grain yields 9 to 11% compared to fall applications of these fertilizer sources. Anhydrous ammonia plus nitrapyrin had grain yields similar to anhydrous ammonia alone at all three application timings. Fall and preplant strip-till placement of PCU increased grain yields 12 to 14% compared to NCU, but no differences in grain yields were detected when fertilizers were applied early preplant. Strip-till placement of PCU and NCU increased yields 26 to 36% over broadcast applications of these fertilizer sources. In this study, enhanced-efficiency fertilizer sources such as PCU increased yields over NCU. Also, placement of PCU in a strip-tilled band synergistically increased yield compared to NCU. Strip-till placement of PCU could provide a fall-applied fertilizer option to fall-applied anhydrous ammonia, but further research should evaluate the leaching potential of such treatments.

Acknowledgments

The authors would like to thank Clinton Meinhardt and Randall Smoot for their technical assistance. The authors wish to express their gratitude to the Missouri Fertilizer and Ag lime distributors for their financial support of this project.

References

Al-Kaisi, M., Licht, M.A., 2004. Effect of strip tillage on corn nitrogen uptake and residual soil nitrate accumulation compared with no-tillage and chisel plow. Agron. J. 96, 1164-1171.

Al-Kaisi, M., Kwaw-Mensah, D., 2007. Effect of tillage and nitrogen Rate on corn yield and nitrogen and phosphorus uptake in a corn-soybean rotation. Agron. J. 99, 1548-1558.

Blaylock, A.D., Binford, G.D., Dowbenko, R.D., Kaufmann, J., Islam, R., 2004. ESN, controlled-release nitrogen for enhanced nitrogen efficiency and improved environmental safety. P 381-390, In Z. Zhu, K. Minami and G. Xing (ed.) 3rd Int. Nitrogen Conf., Nanjing, China. 12-16 Oct. 2004. Science Press and Science Press USA, Monmouth Junction, NJ.

Blaylock, A.D., Kaufmann, J., Dowbenko, R.D., 2005. Nitrogen fertilizer technologies. P 8-13, Western Nutrient Management Conf., Salt Lake City, Utah.

Blevins, D.W., Wilkison, D.H., Kelly, B.P., Silva, S.R., 1996. Movement of nitrate fertilizer to glacial till and runoff from a claypan soil. J. Environ. Qual. 25, 584-593.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Estimation of global NH_3 volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grasslands. Global Biogeochem. Cycles, 16, 1024.

Drury, C.F., Tan, C.S., Reynolds, W.D., Welacky, T.W., Oloya, T.O., Gaynor, J.D., 2009. Managing tile drainage, subirrigation and nitrogen fertilization to enhance crop yields and reduce nitrate loss. J. Environ. Qual. 38, 1193-1204.

Drury, C.F., Reynolds, W.D., Tan, C.S., Welacky, T.W., Calder, W., Mc Laughlin, N.B., 2006. Emissions of nitrous oxide and carbon dioxide: influence of tillage type and nitrogen placement depth. Soil Sci. Soc. Am. J. 70, 570-581.

Drury, C.F., Tan, C.S., Reynolds, W.D., Welacky, T.W., Weaver, S.E., Hamill, A.S., Vyn, T.J., 2003. Impacts of zone tillage and red clover on corn performance and soil physical quality. Soil Sci. Soc. Am. J. 67, 867-877.

Grant, C.A., Derksen, D.A., Mc Laren, D., Irvine, R.B., 2010. Nitrogen fertilizer and urease inhibitor effects on canola emergence and yield in a one-pass seeding and fertilizing system. Agron. J. 102, 875-884.

Halvorson, A.D., Mosier, A.R., Reule, C.A., Bausch, W.C., 2006. Nitrogen and tillage effects on irrigated continuous corn yields. Agron. J. 98, 63-71.

Hendrix, B.J., Young, B.G., Chong, S.K., 2004. Weed management in strip tillage corn. Agron. J. 96, 229-235.

Henry, D.C., Mullen, R.W., Dygert, C.E., Diedrick, K.A., Sundermeier, A., 2010. Nitrogen contribution from red clover for corn following wheat in western Ohio. Agron. J. 102, 210-215.

Jung, W.K., Kitchen, N.R., Sudduth, K.A., Anderson, S.H., 2006. Spatial characteristics of claypan soil properties in an agricultural field. Soil Sci. Soc. Am. J. 70, 1387-1397.

Katsvairo, T.W., Cox, W.J., 2000. Tillage × rotation × management interactions in corn. Agron. J. 92, 493-500.

Licht, M.A., Al-Kaisi, M., 2005a. Corn response, nitrogen uptake and water use in strip-tillage compared with no-tillage and chisel plow. Agron. J. 97, 705-710.

Licht, M., Al-Kaisi, M., 2005b. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res. J. 80, 233-249.

Lithourgidis, A.S., Tsatsarelis, C.A., Dhima, K.V., 2005. Tillage effects on corn emergence, silage yield and labor and fuel inputs in double cropping with wheat. Crop Sci. 45, 2523-2528.

Mehdi, B.B., Madramootoo, C.A., Mehuys, G.R., 1999. Yield and nitrogen content of corn under different tillage practices. Agron. J. 91, 631-636.

Motavalli, P.P., Goyne, K.W., Udawatta, R., 2008. Environmental impacts of enhanced-effi ciency nitrogen fertilizers. Online. Crop Management. doi:10.1094/CM-2008-0730-02-RV.

Myers, D.B., Kitchen, N.R., Sudduth, K.A., Sharp, R.E., Miles, R.J., 2007. Soybean root distribution related to claypan soil properties and apparent soil electrical conductivity. Crop Sci. 47, 1498-1509.

Nelson, K.A., Meinhardt, C.G., 2011. Foliar boron and pyraclostrobin effects on corn yield. Agron. J. 103, 1352-1358.

Nelson, K.A., Motavalli, P.P., Smoot, R.L., 2009a. Dried distillers grain as a fertilizer source for corn. J. Agric. Sci. 1, 3-12.

Nelson, K.A., Paniagua, S.M., Motavalli, P.P., 2009b. Effect of polymer coated urea, irrigation and drainage on nitrogen utilization and yield of corn in a claypan soil. Agron. J. 101, 681-687.

Noellsch, A.J., Motavalli, P.P., Nelson, K.A., Kitchen, N.R., 2009. Corn response to conventional and slow-release nitrogen fertilizers across a claypan landscape. Agron. J. 101, 607-614.

Paulsen, M.R., Pordesimo, L.O., Singh, M., Mbuvi, S.W., Ye, B., 2003. Maize starch yield calibrations with near infrared reflectance. Biosystems Engineering, 85, 455-460.

Paulsen, M.R., Singh, M., 2004. Calibration of a near-infrared transmission grain analyzer for extractable starch in maize. Biosystems Engineering, 89, 79-83.

Randall, G.W., Hill, P.R., 2000. Fall strip-tillage systems. In: R.C. Reeder (ed.) Conservation tillage systems and management. MWPS-45, 2nd ed. Iowa State Univ., Ames, IA. pp. 193-199.

Randall, G.W., Vetsch, J.A., 2005. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by fall and spring application of nitrogen and nitrapyrin. J. Environ. Qual. 34, 590-597.

Randall, G.W., Vetsch, J.A., Huffman, J.R., 2003. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by time of nitrogen application and use of nitrapyrin. J. Environ. Qual. 32, 2447-2447.

Riedell, W.E., Beck, D.L., Schumacher, T.E., 2000. Corn response to fertilizer placement treatments in an irrigated no-till system. Agron. J. 92, 316-320.

Ritchie, S.W., Hanway, J.J., Benson, G.O., 1993. How a corn plant develops. Iowa State Coop. Ext. Serv. Spec. Rep. 48. Ames, IA.

Rochette, P., Angers, D.A., Chantigny, M.H., Mc Donald, J.D., Gasser, M.O., Bertrand, N., 2009a. Reducing ammonia volatilization in a no-till soil by incorporating urea and pig slurry in shallow bands. Nutr. Cycl. Agroecosyst. 84, 71-80.

Rochette, P., Mc Donald, J.D., Aners, D.A., Chantigny, M.H., Gasser, M.O., Bertrand, N., 2009b. Banding of urea increased ammonia volatilization in a dry acidic soil. J. Environ. Qual. 38, 1383-1390.

SAS Institute, 2010. SAS user's guide. SAS Inst., Cary, NC.

Scharf, P.C., Wiebold, W.J., Lory, J.A., 2002. Corn yield response to nitrogen fertilizer timing and deficiency level. Agron. J. 94, 435-441.

Singh, M., Paulsen, M.R., Tian, L., Yao, H., 2005. Site-specific study of corn protein, oil and extractable starch variability using NIT spectroscopy. Applied Engineering in Agriculture, 21, 229-251.

Sommer, S.G., Schjorring, J.K., Denmead, O.T., 2004. Ammonia emission from mineral fertilizers and fertilized crops. Adv. Agron. 82, 557-622.

Torbert, H.A., Potter, K.N., Morrison, J.E., 2001. Tillage system, fertilizer nitrogen rate and timing effect on corn yields in the Texas Blackland Prairie. Agron. J. 93, 1119-1124.

Vetsch, J.A., Randall, G.W., 2004. Corn production as affected by nitrogen application timing and tillage. Agron. J. 96, 502-509.

Vyn, T.J., Faber, J.G., Janovicek, K.J., Beauchamp, E.G., 2000. Cover crop effects on nitrogen availability to corn following wheat. Agron. J. 92, 915-924.

Walters, D.T., Malzer, G.L., 1990. Nitrogen management and nitrification inhibitor effects on nitrogen-15 urea: II. Nitrogen leaching and balance. Soil Sci. Soc. Am. J. 54, 122-130.

Wilson, M.L., Rosen, C.J., Moncrief, J.F., 2009. Potato response to a polymer-coated urea on an irrigated, coarse-textured soil. Agron. J. 101, 897-905.

Zvomuya, F., Rosen, C.J., Russelle, M.P., Gupta, S.C., 2003. Nitrate leaching and nitrogen recovery following application of polyolefin-coated urea to potato. J. Environ. Qual. 32, 480-489.