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Assessing the Benefit of Polymer-Coated Urea for Corn Production on Irrigated Sandy Soils

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ABSTRACT

Polymer-coated urea (PCU) is an enhanced-efficiency fertilizer product that can potentially increase N use efficiency, thereby reducing N losses to the environment. However, the optimum timing and rates of PCU application under varying seasonal precipitation is less known. Here we studied the response of corn (*Zea mays* L.) yield and N use efficiency to N timing (preplant, sidedress, and split application) and rates (112–280 kg N ha^{-1}) of PCU, ammonium sulfate (AS), and urea, including a control treatment without N, on an irrigated sandy soil (90% sand) in central Wisconsin from 2003 to 2006. The effect of N rate on grain yield was significant in 2003, 2004, and 2005, but not in 2006. Grain yield and N recovery efficiency (RE) with preplant PCU was greater in 2004 and 2005, and similar in 2003 and 2006 compared with preplant AS or urea. Preplant PCU had similar or greater yield and RE compared with split-applied AS in 3 yr, but lower yield and RE in the year with the greatest early season rainfall. Nitrification inhibitor (dicyandiamide) showed little impact on corn yield. These results indicated that PCU, when applied preplant, was agronomically and environmentally advantageous over the other N fertilizer sources and typically performed as well as split application of other N fertilizers. However, under conditions where there is a lot of early season rainfall, use of preplant PCU would still result in N losses and then crops would need supplemental N to achieve high yields.

Core Ideas

- Polymer-coated urea led to greater yields compared to other N fertilizers when all applied preplant.
- The performance of preplant polymer-coated urea is reduced in high rainfall years.
- Split application of ammonium sulfate consistently produced the greatest yields on irrigated sands.
- Nitrification inhibitor showed little impact on corn yield on irrigated sandy soils.

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Coarse-textured agricultural soils have low water-holding capacity and high infiltration rates, making irrigation necessary to produce crops but increasing the potential leaching of nitrate to groundwater (Zotarelli et al., 2007). In addition to nitrate-contaminated groundwater, surface waters can also be supplied by shallow aquifers underlying coarse-textured soils, which in turn can affect nitrate concentrations in the entire watershed (Young and Briggs, 2005). Meanwhile, there is evidence of an increase in spring precipitation across the Midwest of the United States which will affect field preparation time in the spring and increase the difficulty in efficiently managing N (Pryor et al., 2013). Recent results from N rate response experiments in the Central Sands of Wisconsin found economically optimum N rates for corn grain were 202 kg N ha^{-1} in a year with low leaching potential compared with 280 kg N ha^{-1} in a year with high leaching potential caused by high early growing season rainfall (Andraski and Bundy, 2005). These results indicated that improved N management practices were essential to avoid excessive N loss and yield reductions in this region.

Enhanced-efficiency fertilizers, and more specifically, controlled-release N fertilizers such as the PCU, have the potential to increase crop N use and reduce N loss (Shaviv, 2001). Polymer-coated urea is a fertilizer product in which each urea prill is individually coated with a polymer (or plastic) coating. Unlike the unprotected urea which rapidly dissolves in water and then converts to ammonium and nitrate, the urea in the PCU dissolves inside the coating and slowly diffuses into the soil over time. By preventing large amounts of ammonium and nitrate from existing in the soil during the early growing season, PCU reduces the potential of volatilization, denitrification, and nitrate leaching, and lessens the need for supplemental N later in the growing season (Shaviv and Mikkelsen, 1993; Shaviv, 2001). Polymer-coated urea has been reported to increase corn (Noellsch et al., 2009; Gagnon et al., 2012) and potato (*Solanum tuberosum* L.) yields (Zvomuya et al., 2003) compared with conventional fertilizers; while some other studies found no benefit in yield at using PCU despite ameliorating nitrate leaching or N_2O emissions (Nelson et al., 2009; Hyatt et al., 2010). This discrepancy demonstrates that the effectiveness of PCU is controlled by many factors including soil type, application rate,

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Abbreviations: AONR, agronomic optimum nitrogen rate; AS, ammonium sulfate; DCD, dicyandiamide; HI, harvest index; NI, nitrification inhibitor; PCU, polymer-coated urea; PNB, partial nutrient balance; pp, preplant; RE, recovery efficiency; UAN, urea-ammonium nitrate.

and seasonal rainfall patterns. It has been suggested that the benefits of PCU may only be achieved when significant environmental and soil constraints (for instance, poor soil structure) exist and cause substantial N loss such as found on sandy soils (Ruark et al., 2018). However, the rate of N release from PCU also depends on soil moisture and temperature which can alter the effectiveness of coatings (Haderlein et al., 2001). The benefits of PCU may be less evident if the timing of N release does not match crop N demand. A better understanding of the effects of inter-annual climatic variation on PCU performance based on timing of application is needed in regards to recommend this N source as a best management practice.

Split application of fertilizer N during the growing season has also been shown to maximize yield and reduce N losses under high early season rainfall (Sitthaphanit et al., 2009; Maharjan et al., 2014; Rubin et al., 2016). In theory, both split application of conventional fertilizers and a single application of PCU synchronize the timing of N availability with plant demand. While split application of fertilizer may conserve N and protect environmental quality, it requires the time and expense associated with additional field applications. Instead, the use of PCU requires fewer or only one application, with a gradual N release over the growing season. However, the PCU is more expensive than conventional fertilizers although the difference in price will vary year to year. In addition to environmental benefits, the impact of these practices on crop yields must also be considered in evaluating their potential for adoption. Several studies have reported advantages of using split vs. single application of conventional N fertilizers on corn yield. Recent research in Minnesota has shown lower corn grain yields where PCU was applied compared with split application of urea (Maharjan et al., 2014; Rubin et al., 2016), while in Nebraska, equal effectiveness of preplant PCU was obtained relative to split-applied urea ammonium nitrate (UAN) (Maharjan et al., 2016a); this discrepancy indicated that the effectiveness of PCU over split application of conventional fertilizers might be affected by other factors such climate, soil type, and fertilizer source used. However, additional research would improve our collective interpretation of the benefit of using PCU.

The objectives of this study were to: (i) determine the response of corn yield, total N uptake, and N use efficiency metrics to different N sources (PCU, AS, and urea) and time of application (preplant, sidedress, or split application) on an irrigated sandy soil in multiple years; and (ii) evaluate changes in agronomic optimum nitrogen rate (AONR) using PCU and AS.

MATERIALS AND METHODS

Experimental Site

The research was conducted from 2003 to 2006 at the University of Wisconsin Agricultural Research Station at Hancock, WI (44°7′ N, 89°32′ W) on an irrigated Plainfield sand soil (mixed, mesic Typic Udipsamment). The site is located in the central sands region of Wisconsin, which is a sandy glacial outwash plain, characterized by deep coarse-textured (90% sand) soils over a relatively shallow water table and encompasses 1×10^6 ha (7% of the state). The soil has low organic matter content (0.8%), pH of 6.7, and a cation exchange capacity of 0.5 to 1.0 cmol kg^{-1} of soil. The average annual temperature of the trial site is 7°C and average annual precipitation is 832 mm (https://enviroweather.msu.edu/weather.php?stn=hck). Intensive crop production, irrigation, and the high leaching potential of soils have resulted in high groundwater nitrate concentrations in the region (Kraft et al., 1999).

Nitrogen Fertilizer Treatments

The experimental design was a randomized complete block-split plot design, with four replications and included a control treatment (no N). Nitrogen source and timing was the main plot treatment, while N rate was the subplot treatment. The N source treatments included: AS with and without a nitrification inhibitor (NI) and a PCU product [Environmentally Smart N (ESN); Agrium Inc., Calgary, AB, Canada] in all years from 2003 to 2006; UAN solution in 2003; and granular urea in 2004 through 2006. All preplant N treatments were surface broadcast applied whereas the sidedress N treatments were subsurface applied and consisted of creating a furrow about 10- to 15-cm deep between the corn rows prior to fertilizer application using tractor-drawn chisel sweeps mounted on a tool bar and closed following fertilizer application with a set of double disks. For the ammonium sulfate with nitrification inhibitor (ASNI) treatment, dicyandiamide (DCD) was surface broadcast applied using a backpack sprayer at a rate of 11.2 kg a.i. ha^{-1} immediately after the AS was surface broadcast applied. Because the AS contains S, a preplant broadcast application of gypsum ($CaSO_4$) providing 44.8 kg S ha^{-1} was made to treatments where the N source was not AS.

Each N source was applied according to different timings. Four application timings were used for PCU: (i) preplant [PCU(pp)], (ii) split application at preplant and 4 wk after planting [PCU(pp4)], (iii) 4 wk after planting [PCU(4)] (2005–2006 only), and (iv) split application at 4 and 6 wk after planting [PCU(46)] (2005–2006 only). Four application timings were used for AS: (i) preplant [AS(pp)]; (ii) split application at 4 and 6 wk after planting [AS(46)], (iii) 4 wk after planting [AS(4)] (2004, 2005, and 2006), and (iv) 6 wk after planting [AS(6)] (2003 only). The AS with NI was applied at preplant [ASNI(pp)]. The UAN was applied at 6 wk after planting [UAN(6)] in 2003 only. Two application timings were used for urea: (i) preplant [UREA(pp)]; and (ii) 4 wk after planting [UREA(4)] in 2004, 2005, and 2006. Nitrogen rates were 112, 168, 224, and 280 kg N ha^{-1} for PCU(pp), PCU(pp4), and AS(46) in all years, and 168 and 224 kg N ha^{--1} for the remaining treatments. Split application [PCU(pp4), PCU(46), and AS(46)] consisted of applying one-half of the total N rate at each time of application. A control treatment (0 kg N ha^{-1}) was also included. The Week 6 fertilizer application was actually conducted in Week 8 in 2003, but referred to as Week 6 throughout the paper for simplicity. A detailed explanation of all treatments in each year as well as the fertilizer application dates are shown in Supplemental Table S1.

Crop Management

The preceding crop was pumpkin (*Cucurbita pepo* L.) in 2003 and potato in 2004, 2005, and 2006. The entire field was moldboard plowed and disked in spring prior to treatment establishment. In late April to early May, the field was disked again following preplant N and gypsum applications to incorporate these materials and prepare the seedbed.

Table 1. Precipitation (P) and irrigation (I) amounts for May to September, 2003 to 2006. Numbers in parentheses are the departure from the 30-yr average.

	2003		2004		2005		2006	
Month	P	I	P	I	P	I	P	I
	mm							
May	117 (34)	38	163 (80)	0	73 (–10)	0	130 (43)	0
June	82 (–11)	64	177 (85)	25	81 (–12)	30	36 (–61)	76
July	54 (–37)	89	72 (–20)	83	142 (51)	130	66 (–25)	155
August	15 (–85)	114	74 (–25)	108	85 (–15)	66	71 (–28)	79
September	70 (–37)	51	13 (–94)	44	99 (–7)	28	84 (–23)	38
Total	338 (–135)	356	499 (26)	260	480 (7)	254	387 (–94)	348

Corn (P37R71) was planted 1 d following seedbed preparation in 91-cm rows at an average density of 78,800 seeds ha^{-1}, and starter fertilizer (112 kg ha^{-1} of 5–10–30) was applied in a band 5.1 cm below and 5.1 cm laterally from the seed at planting to all plots including the control treatment. Individual plots were 10.7 m long and 3.7 m (four rows) wide, while the main plots were 48 m long and 43 m wide. After emergence, plant stands were thinned to a uniform density (average 75,500 plants ha^{-1}). Herbicides were applied to control weeds by the Hancock ARS staff as appropriate.

At physiological maturity (mid-September), six corn plants were hand harvested from each plot to determine total dry matter yield. The samples were collected randomly in harvest rows. The ears including cob and grain were removed, dried at 70°C, shelled, and the dry weights of the cob and grain were recorded. Plants (excluding ears) were weighed, chopped, subsampled, and dried. Corn grain yield was determined by harvesting all ears from the middle two rows from each plot using a plot combine in mid- to late October. Grain yield was reported at a moisture content of 155 g kg^{-1}. All tissue samples were ground to pass a 1-mm screen and analyzed for total N as described by Nelson and Sommers (1973) using automated analysis. Total N uptake was determined as the sum of N uptake in the grain, stover, and cob. Harvest index (HI) was calculated as the ratio of grain to whole plant dry matter. Nitrogen use efficiency metrics included: (i) partial nutrient balance (PNB), calculated as the total N uptake per unit of fertilizer N applied; and (ii) N RE, calculated as the increase in total N uptake in response to fertilizer N application.

Statistical Analysis

Two separate analyses were conducted because some treatments in this 4-yr study received all N rates (0–280 kg N ha^{-1}) while other treatments received only 168 and 224 kg N ha^{-1}. The first analysis was on the dataset with three treatments [PCU(pp), PCU(pp4), and AS(46)] and all N rates (0, 112, 168, 224, and 280 kg N ha^{-1}). The effects of N treatments (source and timing) and fertilizer N rate on grain yield, total N uptake, HI, PNB, and RE were determined separately by year using mixed model (PROC MIXED) in SAS 9.4 (SAS Institute, 2017). Nitrogen treatments and N rate were treated as fixed effects, and block and block ′ system interactions were treated as random effects. To maintain a balanced design, data from the no N control were excluded from the treatment comparison in the ANOVA. For each year, when a significant N treatment or N treatment × N rate interaction was noted in the ANOVA, a regression analysis was conducted using quadratic-plateau model (PROC NLIN) to evaluate the relationship between N rate (including the 0 kg N ha^{-1} rate) and grain yield for PCU(pp), PCU(pp4), and AS(46) and determine the AONR and the yield at AONR. The AONR is the N rate at which the plateau begins. The second analysis tested all N treatments at two N rates (168 and 224 kg N ha^{-1}). The ANOVA using PROC MIXED was conducted in the same manner as described previously. Significant treatment differences were evaluated using a protected least significant difference (LSD) test for main effect means and interactions. A significance level of $\alpha = 0.10$ was used to determine statistical significance in this study.

RESULTS

Growing Season Precipitation

Monthly precipitation and irrigation amounts for the 2003 to 2006 growing seasons are shown in Table 1. Total precipitation from May to September was 338, 499, 480, and 387 mm in 2003, 2004, 2005, and 2006, respectively. Precipitation between preplant N applications through 6-wk sidedress was 133, 366, 162, and 184 mm in 2003 to 2006, respectively. In general, the early season precipitation during the preplant through 6-wk sidedress period was about 54% greater than 30-yr average in 2004, and slightly above 30-yr average in 2005 and 2006.

Nitrogen Source and Rate and Timing Effects on Yield and Agronomic Optimum Nitrogen Rate

The first analysis compared three treatments [PCU(pp), PCU(pp4), and AS(46)] at all N rates (0, 112, 168, 224, and 280 kg N ha^{-1}), and determined AONR and maximum yield. There was a significant effect of N treatment on grain yield in 2003 and a significant effect of N treatment and N treatment × N rate on grain yield in 2004 (Table 2). In 2003, the greatest corn yield was found with PCU(pp) (13.0 Mg ha^{-1}), which was higher than that obtained with AS(46) (11.8 Mg ha^{-1}). In contrast, in 2004 when the greatest early season (preplant to 6 wk) rainfall occurred, AS(46) led to greater corn yield (12.0 Mg ha^{-1}), followed by PCU(pp4) (11.3 Mg ha^{-1}) and PCU(pp) (10.3 Mg ha^{-1}). Significant differences among the N treatments on total N uptake, PNB, and RE were also found in 2004 with AS(46) resulting in the highest values. In 2003, AS(46) resulted in a significantly greater HI than both PCU timings. No significant N treatment effects on corn yield, total N uptake, and N use efficiency metrics were detected in 2005 or 2006 (Table 3).

Corn yield and total N uptake increased significantly with the increase in N rate in 2003, 2004, and 2005, but not in 2006 (Tables 2 and 3). Partial nutrient balance in all 4 yr and RE in 2003, 2005, and 2006 decreased significantly with the increase of N rate. The interaction between N treatments and N rate was significant on RE in 2003 (Table 2, Fig. 1), and on corn yield

Table 2. Mean corn yield, total N uptake, harvest index (HI), partial nutrient balance (PNB), and recovery efficiency (RE) under treatments of PCU(pp), PCU(pp4), and AS(46) in function of N application rates in 2003 and 2004.†

Source of variation	2003					2004				
	Yield	Total N uptake	HI	PNB	RE	Yield	Total N uptake	HI	PNB	RE
	Mg ha^{-1}	kg ha^{-1}		%		Mg ha^{-1}	kg ha^{-1}		%	
Treatment										
PCU(pp)	13.0a‡	200	0.524b	78	63	10.3c	110c	0.493	41c	20c
PCU(pp4)	12.4ab	188	0.529b	73	55	11.3b	146b	0.509	53b	39b
AS(46)	11.8b	185	0.551a	71	54	12.0a	173a	0.511	66a	52a
N rate										
0	6.7	82	0.490	–	–	7.2	73	0.510	–	–
112	11.7c	160d	0.536	103a	68a	10.5c	117c	0.502	73a	39
168	12.3bc	181c	0.531	77b	59b	11.2b	136b	0.500	54b	38
224	13.0a	201b	0.542	63c	53bc	11.5ab	158a	0.510	47c	38
280	12.7ab	222a	0.530	53d	50c	11.7a	161a	0.507	39d	32
ANOVA						*P*-value				
Treatment (T)	0.100	0.364	0.011	0.135	0.359	0.002	0.001	0.224	0.004	0.006
N rate (N)	0.009	<0.001	0.235	<0.001	0.004	<0.001	<0.001	0.720	<0.001	0.294
T × N	0.291	0.299	0.972	0.161	0.091	0.084	0.090	0.799	0.206	0.743

† PCU, polymer-coated urea; AS, ammonium sulfate. pp, preplant; pp4, split-applied at pp and sidedress 4 wk after planting; 46, split sidedress at 4 and 6 wk after planting. All N source treatments received S as gypsum except AS.

‡ Values within each column (excluding the no N treatment) followed by different letters indicate significant differences at $P < 0.10$ level.

and total N uptake in 2004 (Table 2, Fig. 2). Recovery efficiency was significantly greater for PCU(pp) than for the other treatments at the N rate of 112 kg N ha^{-1} in 2003. In 2004, the largest difference in grain yield and total N uptake between AS(46) and PCU(pp) was found at a N rate of 224 kg N ha^{-1}.

Regression models were fit individually for PCU(pp), PCU(pp4), and AS(46) in 2003 and 2004 since there was a significant N treatment effect or N treatment × N rate (Table 4). In 2003, PCU(pp) had the highest potential maximum yield (13.1 Mg ha^{-1}) and the lowest AONR (148 kg N ha^{-1}), while AS(46) had the lowest potential maximum yield (12.3 Mg ha^{-1}) and the highest AONR (231 kg N ha^{-1}). At the opposite, in 2004, AS(46) had the highest potential maximum yield (12.4 Mg ha^{-1}) and the lowest AONR (218 kg N ha^{-1}) among all three treatments, while PCU(pp) had the lowest potential maximum yield (11.1 Mg ha^{-1}) and the highest AONR (280 kg N ha^{-1}). The AONR was quite similar for AS(46) for the 2 yr whereas AONR differed largely between 2003 and 2004 for PCU(pp) with a much higher value to achieve maximum yield in 2004 than in 2003.

Nitrogen Source and Timing Effects on Yield and Nitrogen Use Efficiency

The second analysis compared all treatments across two N rates (168 and 224 kg N ha^{-1}). There was a significant effect of N treatment on yield in 2003, 2004, and 2005, on HI in 2003, 2005, and 2006, and on total N uptake, PNB, and RE in 2004 and 2005 (Tables 5 and 6). In 2003, yields were not significantly different among PCU and AS treatments with the exception of PCU(pp4) > AS(6). Delaying a single AS or UAN application to 6 wk following planting resulted in the lowest yields. In 2004, AS(46) had significantly greater yield, N uptake, PNB, and RE than all other N treatments. The PCU(pp) treatment had significantly less yield, N uptake, and RE compared to PCU(pp4) and AS(4), but significantly greater compared to AS(pp), ASNI(pp), and UREA(pp). The PCU(pp) treatment also had significantly greater yields compared with UREA(4). There was no significant difference in PNB among PCU(pp), AS(pp), and UREA(pp). Corn yield, N uptake, and RE in 2005 was higher for all PCU treatments, in-season or split application of AS and in-season urea than for preplant AS and urea. There was a significant interaction between treatment and N rate on PNB in 2005; the PNB was largely decreased with UREA(pp) at both N rates whereas it was higher at 168 kg N ha^{-1} than at 224 kg N ha^{-1} for the other N treatments (Fig. 3). There was a significant effect of N treatment on HI in 2003 and 2005, but resulting in different effects; the lowest yielding treatment resulted in the highest HI in 2003, but the lowest HI in 2005. When averaged across all N treatments, the 224 kg N ha^{-1} rate resulted in higher yields compared to 168 kg N ha^{-1} in 2004 and 2005, higher N uptake in 2003, 2004, and 2005, lower PNB in all years, and lower RE in 2003, 2005, and 2006. Harvest index was unaffected by N rate.

DISCUSSION

Nitrogen Fertilizer Sources

In this study, PCU generally provided advantages compared to the conventional N fertilizers when applied preplant. Our results showed that, with this N management, PCU had equal or greater yields compared to AS and urea. Rubin et al. (2016) showed that at a rate of 180 kg N ha^{-1} there was no difference in corn yield on an irrigated sandy soil in Minnesota between PCU, urea with urease and nitrification inhibitors, and a 50/50 blend of PCU and urea averaged across 12 site-years. Collectively these results indicated that if limited to one preplant application, using PCU in whole or in part will result in the highest yields, although urease and/or nitrification inhibitor products may work just as well. Nevertheless, in 2004, the year with a high early-season rainfall, PCU(pp) resulted in a higher yield compared to a preplant application of AS with DCD. Interestingly, similar effects of PCU were seen on furrow irrigated fields in Colorado (silty clay soil), where Halvorson and Bartolo (2014) found that PCU, but not stabilized urea, had a grain yield advantage over urea when applied preplant and resulted in a lower AONR and 4 to 14% higher economic return. Zhao et al. (2013) also reported different PCU products resulted in 10 to 14% greater grain yields than

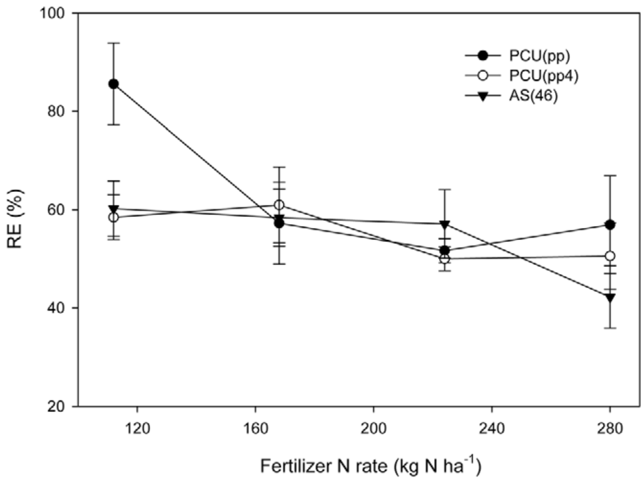

Fig. 1. Recovery efficiency (RE) under treatments of PCU(pp), PCU(pp4), and AS(46) in function of N rates in 2003. PCU, polymer-coated urea; AS, ammonium sulfate. pp, preplant; pp4, split-applied at pp and sidedress 4 wk after planting; 46, split sidedress at 4 and 6 wk after planting.

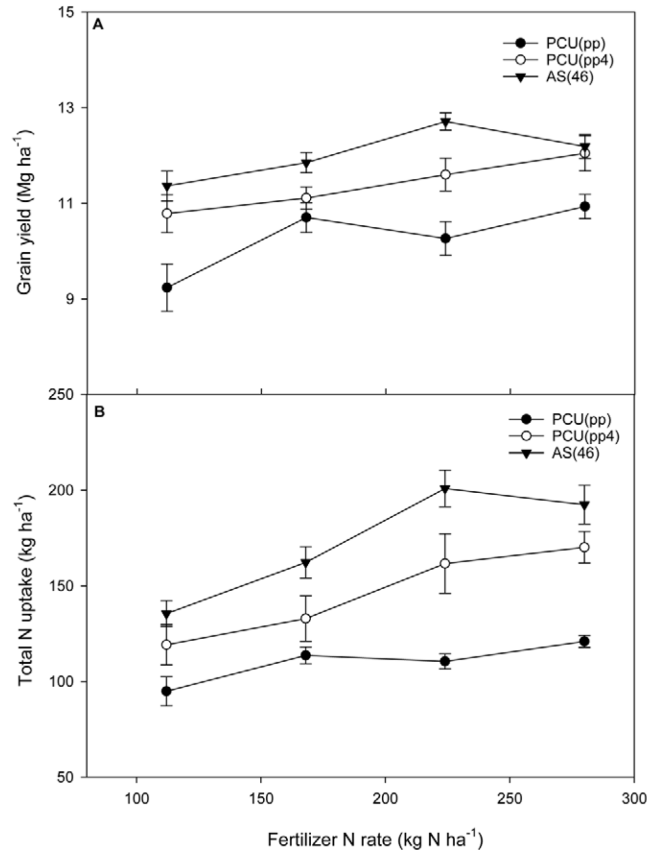

Fig. 2. (A) Corn yield and (B) total N uptake under treatments of PCU(pp), PCU(pp4), and AS(46) in function of N rates in 2004. PCU, polymer-coated urea; AS, ammonium sulfate. pp, preplant; pp4, split-applied at pp and sidedress 4 wk after planting; 46, split sidedress at 4 and 6 wk after planting.

conventional urea on a silt loam soil in eastern China, indicating that the value of PCU can extend to soils across textures.

Nitrogen Fertilizer Timings

In our study, the corn yield response to preplant PCU compared to split application of other N fertilizer sources was variable, but generally positive. Preplant PCU had equivalent or higher yields compared to split-applied AS in 3 out of 4 yr, and at least comparable with a single sidedress application of UAN or granular urea in all years. This contrasts with other studies conducted in the same region. Maharjan et al. (2014) showed that preplant PCU applied at 180 kg N ha^{-1} had lower corn yields compared to split-applied urea across 2 yr in Minnesota. Likewise, Rubin et al. (2016) reported the similar result when averaged across 12 site-years in Minnesota. However, Maharjan et al. (2016b) showed that at 225 kg N ha^{-1} yields between preplant PCU and split-applied urea were similar, but at 180 kg N ha^{-1} yields for preplant PCU were less than split-applied urea. In addition, this study (Maharjan et al., 2016b) indicated that split-applied urea at 180 kg N ha^{-1} resulted in similar yields to preplant PCU at 225 kg N ha^{-1} (in 2009 and 2010),

Table 3. Mean corn yield, total N uptake, harvest index (HI), partial nutrient balance (PNB), and recovery efficiency (RE) under treatments of PCU(pp), PCU(pp4), and AS(46) in function of N application rates in 2005 and 2006.†

Source of variation	2005					2006				
	Yield	Total N uptake	HI	PNB	RE	Yield	Total N uptake	HI	PNB	RE
	Mg ha^{-1}	kg ha^{-1}		%		Mg ha^{-1}	kg ha^{-1}		%	
Treatment										
PCU(pp)	11.5	165	0.558	62	52	11.4	142	0.559	56	46
PCU(pp4)	11.7	168	0.567	68	57	11.6	156	0.560	64	57
AS(46)	11.3	183	0.566	67	58	11.4	156	0.573	61	47
N rate										
0	6.0	68	0.500	–	–	6.0	59	0.500	–	–
112	11.0b‡	144c	0.553b	90a	68a	11.3	140	0.560	89a	68a
168	11.6a	166b	0.567a	69b	58b	11.6	154	0.568	64b	53b
224	11.7a	183a	0.568a	56c	51c	11.3	154	0.560	47c	42c
280	11.7a	192a	0.566a	45d	45d	11.6	158	0.567	39d	36d
ANOVA					*P*-value					
Treatment (T)	0.507	0.178	0.164	0.123	0.166	0.583	0.326	0.600	0.397	0.111
N rate (N)	0.001	<0.001	0.019	<0.001	<0.001	0.632	0.266	0.408	<0.001	<0.001
T × N	0.842	0.285	0.658	0.530	0.276	0.537	0.678	0.323	0.365	0.614

† PCU, polymer-coated urea; pp, preplant; pp4, split-applied at pp and sidedress 4 wk after planting; AS, ammonium sulfate; 46, split sidedress at 4 and 6 wk after planting. All N source treatments received S as gypsum except AS.

‡ Values within each column (excluding the no N treatment) followed by different letters indicate significant differences at $P < 0.10$ level.

Table 4. Corn yield response to applied N for three treatments [PCU(pp), PCU(pp4) and AS(46)] in 2003 and 2004. Δ Max Yield and Δ AONR was the increase/decrease of maximum yield and AONR of PCU(pp) and PCU(pp4) compared to AS(46) treatment.†

Treatment	Equation	R^2	RMSE‡	Max yield	AONR§	Δ Max Yield	Δ AONR
				Mg ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	kg N ha^{-1}
2003							
PCU(pp)	$y = 6.70 + 0.0864x - 0.00030x^2$	0.976	0.630	13.1	148	0.8	−83
PCU(pp4)	$y = 6.69 + 0.0607x - 0.00020x^2$	0.994	0.296	12.7	199	0.4	−32
AS(46)	$y = 6.73 + 0.0479x - 0.00010x^2$	0.973	0.554	12.3	231	–	–
2004							
PCU(pp)	$y = 7.21 + 0.0250x - 0.00004x^2$	0.948	0.487	11.1	280	−1.3	62
PCU(pp4)	$y = 7.29 + 0.0369x - 0.00008x^2$	0.983	0.354	11.8	245	−0.6	27
AS(46)	$y = 7.26 + 0.0469x - 0.00010x^2$	0.987	0.351	12.4	218	–	–

† PCU, polymer-coated urea; pp, preplant; pp4, split-applied at pp and sidedress 4 wk after planting; AS, ammonium sulfate; 46, split sidedress at 4 and 6 wk after planting.

‡ RMSE, root-mean-square error.

§ AONR, agronomic optimum N rate.

suggesting that in this circumstance split-applied urea might achieve the same yield at a lower N rate compared with preplant PCU. These findings from central Minnesota contrast with those from Nebraska (irrigated sand) which showed a single, post-planting application of PCU (13–30 d after corn planting) significantly increased grain yield compared to application of UAN at the same time (Maharjan et al., 2016a). In addition, post-planting 168 kg N ha^{-1} of PCU resulted in similar yields as split application of UAN (30% post planting and 70% at the V6 growth stage) at a rate of 196 kg N ha^{-1}.

Rainfall amounts and patterns may explain some of the variation among treatments reported in these studies. Researches in Minnesota (Maharjan et al., 2014; Rubin et al., 2016) were conducted under higher seasonal (May–September) rainfall conditions (398–595 mm, mean = 474 mm; 2009–2014) compared to those in Nebraska (242–579 mm, mean = 427 mm; 2009–2011; Maharjan et al., 2016a) and in this study (338–499 mm, mean = 426 mm). This suggests that the performance of preplant N application, even as PCU, would be affected by high early-season rainfall. Within our study, the year with the greatest rainfall (2004) was also the year where PCU did not perform as well as split-applied conventional fertilizers. More specifically, our study also suggests that the pattern of rainfall is also a driver of the effectiveness of PCU. In 2004, the rainfall amount during the 6-wk period following planting was 100 to 172% greater than other years (Table 1). The abundance of early-season soil moisture likely accelerated the diffusion process of the urea-N through the polymer coating, which is affected by both soil temperature and moisture (Haderlein et al., 2001). A potential increase in diffusion from the coating combined with high rainfall amounts likely cause the transport of N out of the root zone. Interestingly, Halvorson and Bartolo (2014) showed

Table 5. Mean corn yield, total N uptake, harvest index (HI), partial nutrient balance (PNB), and recovery efficiency (RE) under all treatments at a N input rate of 168 and 224 kg N ha^{-1} in 2003 and 2004.

Source of variation	2003					2004				
	Yield	Total N uptake	HI	PNB	RE	Yield	Total N uptake	HI	PNB	RE
	Mg ha^{-1}	kg ha^{-1}		%		Mg ha^{-1}	kg ha^{-1}		%	
Treatment†										
PCU(pp)	12.8ab‡	188	0.525cd	69	55	10.5c	112c	0.500	40d	21c
PCU(pp4)	12.9a	189	0.533bc	71	56	11.4b	147b	0.509	48c	38b
AS(pp)	12.4ab	204	0.491e	69	64	8.3e	97de	0.534	36d	12de
AS(4)	–	–	–	–	–	11.3b	153b	0.505	54b	41b
AS(6)	11.9bc	192	0.568a	68	57	–	–	–	–	–
AS(46)	12.2abc	195	0.551ab	70	58	12.3a	182a	0.506	64a	55a
ASNI(pp)	12.7ab	210	0.509de	70	65	8.5 e	92e	0.510	32e	10e
UAN(6)	11.3c	186	0.566a	67	54	–	–	–	–	–
UREA(pp)	–	–	–	–	–	8.9e	96de	0.515	36d	12e
UREA(4)	–	–	–	–	–	9.5d	110cd	0.488	38d	19cd
N rate										
168	12.2	187b	0.534	77a	63a	9.8b	116b	0.506	48a	26
224	12.3	202a	0.535	61b	54b	10.4a	131a	0.510	39b	26
ANOVA						*P*-value				
Treatment (T)	0.093	0.452	<0.001	0.977	0.505	<0.001	<0.001	0.126	<0.001	<0.001
N rate (N)	0.567	0.005	0.892	<0.001	0.002	<0.001	0.001	0.546	<0.0011	0.950
T × N	0.240	0.122	0.321	0.756	0.210	0.154	0.122	0.974	0.690	0.834

† PCU, polymer-coated urea; pp, preplant; pp4, split-applied at pp and sidedress 4 wk after planting; 4, sidedress 4 wk after planting; AS, ammonium sulfate; ASNI, AS with nitrification inhibitor; UAN, urea-ammonium nitrate; 46, split sidedress at 4 and 6 wk after planting; 6, sidedress applied at 6 wk after planting. All N source treatments received S as gypsum except AS.

‡ Values within each column followed bydifferent letters indicate significant differences at $P < 0.10$ level.

Table 6. Mean corn yield, total N uptake, harvest index (HI), partial nutrient balance (PNB), and recovery efficiency (RE) under all treatments at a N input rate of 168 and 224 kg N ha^{-1} in 2005 and 2006.

Source of variation	2005					2006				
	Yield	Total N uptake	HI	PNB	RE	Yield	Total N uptake	HI	PNB	RE
	Mg ha^{-1}	kg ha^{-1}		——— % ———		Mg ha^{-1}	kg ha^{-1}		——— % ———	
Treatment†										
PCU(pp)	11.7ab‡	169a	0.561bc	60ab	52a	11.4	148	0.560bc	54	47
PCU(pp4)	11.9a	175a	0.568ab	64a	55a	11.4	160	0.556c	57	53
PCU(4)	11.6ab	175a	0.576a	62ab	56a	11.1	148	0.584a	54	47
PCU(46)	11.5ab	172a	0.568ab	63ab	54a	11.0	156	0.562bc	55	51
AS(pp)	11.0c	153b	0.550cd	56c	43b	11.3	147	0.547c	51	47
AS(4)	11.3bc	173a	0.563bc	61ab	54a	11.0	141	0.587a	51	42
AS(46)	11.5abc	179a	0.574ab	63ab	57a	11.5	154	0.578ab	55	43
ASNI(pp)	11.5ab	176a	0.540de	62ab	56a	11.9	163	0.558c	57	54
UREA(pp)	9.6d	120c	0.535e	42d	27c	11.4	143	0.563bc	54	44
UREA(4)	11.3abc	167ab	0.571ab	60b	51ab	11.3	149	0.575ab	53	47
N rate										
168	11.1b	158b	0.559	66a	54a	11.4	149	0.569	62a	52a
224	11.5a	173a	0.562	53b	47b	11.3	152	0.565	46b	41b
ANOVA					*P*-value					
Treatment (T)	<0.001	<0.001	<0.001	<0.001	<0.001	0.223	0.171	0.011	0.650	0.175
N rate (N)	<0.001	<0.001	0.487	<0.0011	<0.001	0.585	0.458	0.444	<0.001	<0.001
T × N	0.117	0.955	0.866	0.041	0.635	0.790	0.835	0.818	0.891	0.975

† PCU, polymer-coated urea; pp, preplant; pp4, split-applied at pp and sidedress 4 wk after planting; 4, sidedress 4 wk after planting; 46, split sidedress at 4 and 6 wk after planting; AS, ammonium sulfate; ASNI, AS with nitrification inhibitor. All N source treatments received S as gypsum except AS.

‡ Values within each column followed by different letters indicate significant differences at $P < 0.10$ level.

an advantage of preplant PCU when growing season rainfall was between 131 and 260 mm, but excessive rainfall or irrigation may also accelerate the diffusion process of urea N and this should be avoided. Collectively, these results suggest that the value of PCU will occur in years with less early-season rainfall following its application, rather than high rainfall as the capacity of the polymer was not sufficient to reduce export out of the root zone in these years. Although less rainfall does not necessarily imply that there is insufficient water for diffusion from the polymer coating to occur; excessive irrigation may also accelerate the diffusion process of the urea N through the polymer-coating.

Across the studies on irrigated, sandy soils comparable to central Wisconsin, there was not a yield increase of PCU over split application of conventional N fertilizers, but this can serve to achieve the same yield with less number of applications. Furthermore, ASNI(pp) did not show benefits over AS(pp), but resulted in significantly lower corn yield and N use efficiency than AS(46) in 2004, suggesting that in years with high early rainfall, adding DCD was not as effective as split application of conventional fertilizers. Although DCD has advantages such low cost and less volatile, it is more soluble and mobile than other nitrification inhibitors such as 3,4-dimethylepyrazole phosphate (DMPP) and can easily get lost after early season rainfall (Benckiser et al., 2013; Abalos et al., 2014).

Split application and timing of PCU application is not well studied. Our results suggest that split application of PCU (preplant and 4 wk) was not sufficient to maintain yields relative to AS46 in 2004, the year with the greatest rainfall, although it did improve yields over preplant PCU. In 2005 and 2006, additional timings and split application of PCU were included in the study. In these years, there was no difference among any of the PCU timing treatments and split application of AS. These results suggest that additional research is necessary on timing and rate of PCU. There is also a lack of information related to blending of PCU with other N fertilizer sources. Blending PCU with other N sources like urea could be a better approach on irrigated sandy soils when early rainfall exceeds normal average. In addition, the PCU is usually 15 to 30% more expensive than urea although the price is volatile and may vary year to year (Hopkins et al., 2008; Wilson et al., 2009). This price difference between PCU and conventional fertilizers must be considered against economic gains of yield and reduction of transportation costs with a reduction of number of applications.

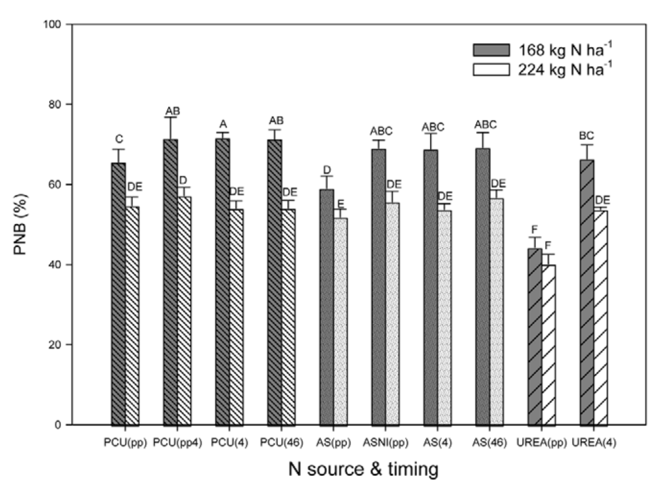

Fig. 3. Partial nutrient balance (PNB) of all treatments under N input rates of 168 and 224 kg N ha^{-1} in 2005. PCU, polymer-coated urea; AS, ammonium sulfate; ASNI, AS with nitrification inhibitor. pp, preplant; pp4, split-applied at pp and sidedress 4 wk after planting; 4, sidedress 4 wk after planting; 46, split sidedress at 4 and 6 wk after planting.

Agronomic Optimum Nitrogen Rate and Maximum Yield

Selection of appropriate N fertilizer rate is important for the profitability of corn production and environmental sustainability. The regression analysis provides a quantitative value regarding the differences in optimum N rate. Few studies evaluated PCU across sufficient N rates to determine optimum N rates through non-linear regression. Both Maharjan et al. (2016b) and Rubin et al. (2016) assessed AONR of corn yield through quadratic-plateau regression based on 45 to 315 kg N ha^{-1} of urea on a loamy sand soil, but only compared corn yield from PCU and other N sources at 180 and 225 kg N ha^{-1}. Direct comparison of PCU to other N sources using nonlinear regression would lead to more clarity as to the full economic effect of PCU use. In our study, 2 yr out of 4 provided AONR determination through regression analysis. The AONR was comparable between years for split-applied AS but it differed widely for PCU preplant likely due to early rainfall (–83 kg N ha^{-1} in 2003 compared with AS for a normal year and +62 kg N ha^{-1} in 2004 for a wet year).

This study also indicated that RE varied largely from year to year. Across all N source treatments applied at 168 kg ha^{-1} (Tables 5 and 6), RE ranged from 26 to 63%, averaging 49%. These values are similar to those of Rubin et al. (2016) who reported an average RE of 52% with urea and 45% with PCU and by Maharjan et al. (2016a) who reported an average RE of 51% with PCU and 39% with split application of UAN. We had much lower N uptake with no N applied (59–83 kg ha^{-1}) compared to Rubin et al. (2016) (126 kg ha^{-1}), and lower yields and uptake in fertilized plots. Our data, along with other recent studies, highlight the challenge to managing N on sandy soils. Unrecovered N will likely be leached; greater RE needs to be obtained to achieve substantial improvements in groundwater quality. PCU can play a role in improving the RE, but use of PCU alone does not guarantee high RE.

CONCLUSION

Our study revealed that N source and timing could affect corn yield and N use efficiency on irrigated, sandy soil which was highly dependent on the amount of early-growing season rainfall. If using a single preplant application, PCU was agronomically advantageous over the other fertilizer N sources. A single preplant PCU application was as effective as sidedress or split application of AS or urea in years with normal- or below-average precipitation, and performed better than preplant application of other conventional fertilizers (AS and urea) in wet years. However, split application of AS are superior in high rainfall years where preplant PCU could result in an increased risk of N loss and the need for supplemental N.

SUPPLEMENTAL MATERIAL

Table S1. Nitrogen fertilizer sources and timings applied each year from 2003 through 2006. Shaded grids mean application of N fertilizer at certain N rate.

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