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Pre-Plant and In-Season Nitrogen Combinations for the Northern Corn Belt

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ABSTRACT

In-season N applications offer greater flexibility to address climate variability and better synchronize N availability with corn (*Zea mays* L.) uptake, but deliberating between V4 vs. V11 sidedress (SD) application requires validation. A six site-year study investigated multiple N placement and timing strategies on corn growth, yield, and profitability. The three primary strategies involved pre-plant incorporated (PPI), in-furrow (IF) (7.8 kg N ha^{-1}), or subsurface banded N fertilizer below the furrow (5×5) (45 kg N ha^{-1}). Treatment combinations within the IF and 5×5 starter N strategies included SD at V4, V11, or 50:50 (split) V4 and V11. The PPI strategies involved 100% urea, 25:75 blend of urea with polymer-coated urea, and poultry litter applied at 2.2 Mg ha^{-1} plus SD N at V11. There were few yield and profitability benefits to late-season N application. The 5×5 strategy stabilized both yield and profit variability whereas the IF strategy occasionally reduced yield when SD was delayed from V4 to V11. Split N applications (i.e., multi-pass) increased yield 4.4 to 16.1% compared with a one-pass PPI strategy in 4 of 6 site years. Increased starter N rates (>45 kg N ha^{-1}) may be required when full SD is applied at V11 but N source must be cost effective. When using IF and 5×5 strategies at N rates in the current study, in-season SD N applications were required prior to V11. The V11 timing may be considered as a rescue application in northern corn regions but not standard practice.

Core Ideas

- Starter fertilizer strategies must sufficiently supply N until sidedress time to influence success of in-season N application.
- Applying the majority of N at V11 did not increase yield potential and may be best utilized as a rescue application in the northern Corn Belt.
- Increased 5×5 starter N rates (>45 kg N ha^{-1}) may be required when full SD is applied at V11 to maintain yield potential.
- In variable weather conditions splitting N applications (i.e., multi-pass systems) improved synchrony of N application with corn N uptake.

Spring pre-plant N applications are considered a best-management practice in conventionally tilled, poorly drained, medium- to fine-textured soils throughout the northern Corn Belt (Vetsch and Randall, 2004). Corn (*Zea mays* L.) yield potential is affected by a multitude of agronomic practices (e.g., fertility management), cultivars, and the environment (Evans and Fischer, 1999). Recent data project more frequent heat waves (i.e., >5°C above climatic normal) and increasing air temperatures (1.5–2.0°C) over the next 30 yr that may affect spring frost dates in the northern hemisphere and increase precipitation intensity during winter and spring months (>50.8 mm in 48 h) (Hayhoe et al., 2007; Karl et al., 2009). Warmer spring temperatures may shift corn planting dates earlier than currently recommended (Lauer et al., 1999). Weather variability may increase risk of early applied N losses (i.e., volatilization, leaching, and denitrification) and require reexamination of N management strategies (Scharf et al., 2002). Optimal soil fertility management includes adjusting strategies to account for the proper placement, time, source, and rate (e.g., 4R) of N adapted to site- or region-specific environments (Roberts, 2007). Rapid corn N uptake does not occur until the V10 growth stage (Bender et al., 2013). Delayed sidedress (SD) N applications (e.g., after V10) may help mitigate the time lapse between N application and uptake but further research is needed to refine current grower practices.

Pre-plant incorporation (PPI) is a one-pass N strategy where 100% of the N inputs are applied up to planting time and incorporated. A large percentage of Michigan corn land area is grown on calcareous soils with a soil pH > 7.2, which can increase NH_3 volatilization losses, increase N immobilization, and reduce the efficiency of surface-applied urea containing N fertilizers (Havlin et al., 2014). In Michigan studies, blending polymer-coated urea (PCU) with urea (75:25, PCU/urea blend ratio) has improved efficiency of urea containing fertilizers. For example, when April and May precipitation were above average, PCU/urea broadcast 2 to 4 wk before planting and incorporated improved corn yield up to 1.38 Mg ha^{-1} relative to 100% urea PPI (Franzen, 2017). In the same studies a PCU/urea blend extended N activity in dry soils, which increased corn grain yield 1.07 Mg ha^{-1} relative to a V4 to V6 surface

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Abbreviations: 5×5, subsurface banded N application 5 cm below and 5 cm laterally; CM, chlorophyll meter; IF, in-furrow; NDVI, normalized difference vegetation index; PCU, polymer-coated urea; PL, poultry litter; PPI, pre-plant incorporated; SCRF, South Campus Research Farm; SD, sidedress; SVREC, Saginaw Valley Research and Extension Center; UAN, urea ammonium nitrate.

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banded SD application. Although spring pre-plant N applications to medium and fine-textured soils in the northern Corn Belt are a best management practice, above-average precipitation in April, May, and June may increase the risk for N loss (Vetsch and Randall, 2004). In Minnesota, a single spring pre-plant N applications reduced corn grain yield 0.39 Mg ha^{-1} relative to split applications (Randall et al., 2003). In Michigan, corn grain yield was reduced 2.45 Mg ha^{-1} relative to a single at-plant N application (Franzen, 2017). Reduced efficiency of one-pass N strategies has prompted some growers to utilize a multi-pass system to improve N recovery (Warncke et al., 2009).

Starter fertilizers used to split-apply N may improve synchrony between N application and plant N uptake. In-furrow (IF) nutrient placement (i.e., "popup" or "seed-placed" starter) provides immediate nutrient access to emerging corn roots as fertilizer is placed with the seed at planting (Niehues et al., 2004). The IF placement is popular in the northern Corn Belt because of less planter equipment required (Kaiser et al., 2016). However, to prevent yield reduction due to seedling injury or delayed emergence, reduced fertilizer rates and non-urea forms of N are required to avoid excessive salt concentrations or ammonia toxicity (Raun et al., 1986; Rehm and Lamb, 2009). Michigan IF corn fertilizer recommendations include ≤5.6 kg N+ K_2O ha^{-1} where CEC is <7 $cmol_c$ kg^{-1} and ≤9.0 kg N+K_2O ha^{-1} where CEC is ≥8 $cmol_c$ kg^{-1} (Steinke, 2013). In-furrow starter fertilizer has increased early season plant height and kernel mass but decreased grain moisture and number of days to silking (Kaiser et al., 2016). Despite increased early season plant growth, IF applications may not correlate to grain yield ($r = 0.44$) (Bermudez and Mallarino, 2002, 2004). In-furrow starter fertilizers sometimes contain P, K, or an N–P–K combination. Positive grain yield responses from IF fertilizer were attributed to the P-component in soils testing low in phosphorus (soil test P, STP) (<16 mg P kg^{-1}, Bray-1 test) and attributed to the N-component in high STP soils (>23 mg kg^{-1}) (Bermudez and Mallarino, 2002, 2004). In corn production regions with compressed growing seasons and shorter maturity length hybrids (i.e., Michigan), data on fertilizer strategies that provide minimal early season N in favor of later N applications are minimal and require further investigation.

Subsurface banded N application 5 cm below and 5 cm laterally (5×5) relative to the seed furrow is another strategy to encourage early season plant growth and nutrient uptake. The 5×5 placement requires installation of an extra planting coulter that may reduce planting speed and be more affected by soil moisture than the IF strategy. However, the 5×5 placement can utilize multiple N sources and allows greater flexibility for N rate selection relative to IF placement (Niehues et al., 2004). Corn V6 plant biomass and grain yield have increased more consistently with no-till 5×5-placed starter fertilizer relative to IF placements in Illinois (Ritchie et al., 1996). In Missouri no-till soils, 5×5 placement increased yield 0.82 Mg ha^{-1} relative to a no 5×5 control (Scharf, 1999). In Wisconsin, 5×5 placed starter fertilizer increased yields up to 0.70 Mg ha^{-1} relative to a no starter control across multiple tillage regimes (Wolkowski, 2000). When compared with IF placement, positive yield responses to the 5×5 placement have been attributed to reduced seedling injury and increased 5×5 N rates (16.3–27.2 kg N ha^{-1}) (Lamond and Gordon, 2001; Bermudez and Mallarino, 2002). Corn response to 5×5 starter may also depend on the interaction between growing season length and hybrid maturity class. On Missouri silt-loam soils, increased early corn growth and reduced days to silking were attributed to hybrid maturity class, tillage, and 5×5 starter application but grain yield was not affected (Cromley et al., 2003, 2006). Bundy and Andraski (1999) observed that a positive yield and economic response to 5×5 starter was positively correlated ($R^2 = 0.51$) to the sum of hybrid relative maturity (RM) and planting date in Julian days (PD) and most likely when RM + PD > 235. A 5×5 starter response observed by Bundy and Andraski (1999) was attributed to stimulation of early corn growth leading to increased yield potential (Bundy and Andraski, 1999). Few data exist comparing the 5×5 strategy with multiple SD application timings in the northern Corn Belt.

Growers who split-apply N often utilize SD applications up until the V6 growth stage, but interest in delayed (i.e., post-V6) N applications has increased (Binder et al., 2000; Scharf et al., 2002). Corn N uptake does not accelerate until V6 to V8 (Bender et al., 2013). However, weather, planting date, and fertilizer application strategy may affect the ability of a developing corn plant to uptake N and increase the potential for N stress prior to SD time resulting in reduced yield potential (Bundy and Andraski, 1999; Scharf et al., 2002). When compared with at-plant N applications, N applied at V8 increased N recovery 11% at rates between 75 and 150 kg N ha^{-1} (Jokela and Randall, 1997). In Missouri, Scharf et al. (2002) did not observe a yield loss when N was delayed until V11 but noted a 0 to 3% reduction with N applied V12 to V16. Delayed N applications may, however, have less effect on plant growth and development in the midwestern U.S. Corn Belt as compared with northern production regions where fewer suboptimal growing days may exert greater influence on growth and development (Scharf et al., 2002). Nitrogen stress due to late N application emphasizes the importance of satisfying early season corn N requirements and the need to identify corn response to delayed sidedress N applications. The positional N availability of strategies including IF and 5×5 starter fertilizer offer opportunities to reduce N rates applied at planting. However, the increased N rate afforded by the 5×5 strategy as compared with IF may enable N sufficiency until V11 SD. Poultry litter is a slowly mineralizable N source and may provide sufficient N until V11 SD. The objective of this study was to investigate the effects of sidedress N application timing in combination with starter N (IF or 5×5) and PPI N on corn growth, grain yield, and profitability.

MATERIALS AND METHODS

Field trials were conducted from 2014 to 2016 at the Saginaw Valley Research and Extension Center (SVREC) (43°23′58.2″ N, −83°41′52.7994″ W) in Richville, MI, on a Tappan-Londo loam soil (fine-loamy, mixed, active, calcareous, mesic Typic Epiaquolls) and at the South Campus Research Farm (SCRF) (42°40′24.24″ N, −84°29′13.1994″ W) in Lansing, MI, on a Capac loam soil (fine-loamy, mixed, active, mesic Aquic Glossudalf). Fields were autumn chisel plowed following soybean [*Glycine max* (L.) Merr.] harvest and followed with spring tillage using a soil finisher to a 10-cm depth. Soil samples were collected for P, K, pH, and organic matter analysis to a depth of 20 cm prior to fertilizer application, air-dried, and ground to pass through a 2-mm sieve. Soil characteristics at SVREC were 7.6 to 7.7 pH (1:1, soil/water) (Peters et al., 2015), 19 to 24 mg kg^{-1} P

(Bray-P1) (Frank et al., 2015), 138 to 164 mg kg^{-1} K (ammonium acetate method) (Warncke and Brown, 2015), and 27 to 28 g kg^{-1} soil organic matter (loss-on-ignition) (Combs and Nathan, 2015). Soil characteristics at SCRF were 6.5 to 6.8 pH, 25 to 47 mg kg^{-1} P, 91 to 114 mg kg^{-1} K, and 28 to 34 g kg^{-1} soil OM. Broadcast P and K fertilizer were pre-plant incorporated (10-cm depth) prior to planting as monoammonium phosphate (MAP) (11–52–0, N–P–K) and muriate of potash (MOP) (0–0–62) based on soil tests. Weed control at SVREC consisted of S-metolachlor (acetamide, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)-,(S)) and glyphosate (N-(phosphonomethyl) glycine) (6 June 2014, 28 May 2015 [glyphosate only], and 9 June 2016) followed by a second application of glyphosate (20 June 2014 and 22 June 2015). Weed control at SCRF consisted of S-metolachlor and glyphosate (10 June 2014), acetochlor (2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide) and glyphosate (defined previously) (2 June 2015 and 10 June 2016) followed by a second application of glyphosate (26 June 2014, 26 June 2015, and 27 June 2016). Environmental data were collected throughout the year using the Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI; accessed 24 July 2017) from an on-site weather station.

Ten treatments including a non-fertilized control were arranged in a randomized complete block with four replications. Treatments were equalized to a total N rate based on the site-specific maximum return to nitrogen rate (MRTN) (202 and 157 kg N ha^{-1} for SVREC and SCRF, respectively) (Sawyer et al., 2006). Three treatment strategies were utilized and included: (i) PPI N, (ii) IF starter N (7.8 kg N ha^{-1} ammonium polyphosphate [10–34–0]), and (iii) starter N 5×5 (45 kg N ha^{-1} urea ammonium nitrate [UAN, 28–0–0]). Treatments within the PPI N strategy included (i) 100% urea (46–0–0), (ii) 25:75 mix of urea with polymer-coated urea (PCU) (44–0–0, N–P–K, Agrium, Calgary, AB, Canada), and (iii) dried poultry litter (PL) (4–3–2) applied at 2.2 Mg ha^{-1} plus SD N V11. Treatment combinations within the IF and 5×5 N strategies included SD at (i) V4, (ii) V11, or (iii) a 50:50 split at V4 and V11. Corn V4 N was UAN coulter injected 5 cm deep and 38 cm to the side of each row (Ritchie et al., 1997). Corn V11 N was UAN mixed with a urease inhibitor ($CO(NH_2)2$ + n-(n-butyl) thiophosphoric triamide) (Koch Agronomic Services, LLC, Wichita, KS) to prevent N volatilization and banded 10 to 15 cm to the side of each row. A non-limiting N reference (280 kg N ha^{-1}) was included to normalize canopy sensor data. An untreated control, which did not receive N fertilizer, was also included. Plot width was 4.5 m and plot length was 12.1 m. A Monosem planter (Monosem, Kansas City, KS) equipped with Yetter floating planter-unit mounted row cleaners (Yetter Manufacturing, Colchester, IL) and liquid fertilizer applicators was used to apply IF and 5×5 starter. All locations used Dekalb DKC48-12 RIB (98 d relative maturity) (mid-season hybrid) (Monsanto Co., St. Louis, MO) planted in 76-cm rows at 84,510 seeds ha^{-1} (Table 1).

Corn plant density (V3) was determined as number of corn plants in both harvest rows expressed as plants per ha^{-1}. Canopy normalized difference vegetation index (NDVI) at V6 and V11 was collected using a GreenSeeker Model 505 handheld red-band optical sensor (Trimble Agriculture Div., Westminster, CO). Ear leaf N status was determined with a Minolta SPAD 502 chlorophyll meter (CM) (Konica Minolta, Tokyo, Japan) and normalized to the non-limiting N reference per replicate (Shapiro et al., 2013). The center two rows of each plot were harvested with a research plot combine to determine grain yield, moisture, and test weight. Yield data were reported at 155 g kg^{-1} moisture. Treatment profitability was calculated as net return = gross return from yield – input costs (Table 2).

Table 1. Corn planting and sidedress N application dates for SCRF (Lansing, MI) and SVREC (Richville, MI), 2014–2016.

	SCRF			SVREC		
Year	Planting	V4	V11	Planting	V4	V11
2014	19 May	9 June	7 July	8 May	4 June	30 June
2015	1 May	2 June	29 June	28 Apr.	28 May	25 June
2016	18 May	6 June	5 July	9 May	3 June	29 June

Data were subject to analysis of variance using the GLIMMIX procedure in SAS assuming fixed effects of site, year, and treatment with random block effects (SAS Institute, 2011). The UNIVARIATE procedure was used to test for normality of residuals ($P \le 0.05$). Levene's test was used to investigate homogeneity of error variances using squared- and absolute-values of residuals ($P \le 0.05$). The LINES option of the slice statement was used to separate least squares means (LS-means) when ANOVA indicated a significant interaction ($P \le 0.10$). Multiple degree of freedom (df) contrasts were constructed to compare means across N strategies or between one and multi-pass systems. To compare strategies, means were a combination of three treatments within each N strategy (e.g., the 5×5 strategy included a mean of three sidedress treatments that received 5×5 starter fertilizer) while comparison of systems were made using a combination of the PCU and PCU/urea treatment (i.e., one-pass system) and all other treatments (i.e., multi-pass system). Pearson product-moment correlations were used to investigate the relationship of canopy sensor data, profitability, and treatment costs with grain yield ($P \le 0.05$) using the CORR procedure.

RESULTS AND DISCUSSION

Growing Conditions

Total growing season (April–September) precipitation differed by −9, 20, and 1% and 4, −19, and −26% from the 30-yr mean during 2014–2016 at Lansing and Richville, MI, respectively (Table 3). May and June 2015 precipitation in Lansing was 24 and 103 mm greater than the 30-yr mean, but 2014–2016 May and June precipitation in Richville was deficient by 6 to 44 mm and 20 to 52 mm, respectively. Cumulative April to June rainfall was >10% above the 30-yr mean (i.e., excessive) in Lansing 2015 and resulted in wet soils, and <10% (i.e., deficit) in Richville 2015–2016 and Lansing 2016 and resulted in dry soils. August precipitation was 2 to 79 mm above the 30-yr mean across all site years. Mean April air temperatures were below the 30-yr mean across all years and locations whereas May and June air temperatures were within 0.3 to 1.6°C at each location. In July 2014 air temperatures were 3.1 to 3.3°C below the 30-yr mean at each location. August and September mean air temperatures were within 0.5 to 2.2°C of the 30-yr mean across all site years.

Corn Plant Density

Means were combined across treatments within each strategy (i.e., IF, PPI, and 5×5) as no SD N applications occurred before

Table 2. Prices received and variable input costs utilized used for profitability analysis, 2014–2016.

Investments	Returns	2014	2015	2016
		US$ Mg^{-1}		
Prices received†	Corn	138.18	142.91	131.88
	Costs	US$ kg^{-1}		
Fertilizer‡	Urea N	1.20	1.01	0.74
	28% UAN	1.26	1.14	0.81
	10–34–0	5.68	7.19	6.17
	PCU	1.63	1.54	1.23
	Poultry litter (PL)	3.78	4.23	4.23
		US$ L^{-1}		
N stabilizer§	Urease inhibitor	19.01	19.01	19.01
		US$ ha^{-1}		
Application¶	5×5 fertilizer applicator	5.24	5.12	4.99
	Urea broadcast application	17.27	14.65	15.59
	Urea incorporation	15.96	17.54	21.62
	UAN injection application (V4)	27.63	31.88	30.32
	UAN high-clearance application (V11)	19.00	25.03	22.76
	Grain hauling#	0.32	0.32	0.32

† Autumn grain prices for each year.

‡ Spring urea and UAN prices for each year; PL, 10–34–0, and PCU prices obtained from local vendors.

§ Urease inhibitor price obtained from local vendors and applied at label rates.

¶ Application costs obtained from Michigan State University Extension custom machine and work rate estimates for each year (http://msue.anr.msu.edu/topic/farm_management/firm_publication_archive, Michigan State University, East Lansing, MI; accessed 23 May 2017).

Grain hauling for field to farmstead or farmstead to market up to 40 km.

Table 3. Growing season (April–September) and 30-yr mean temperature† (°C) and precipitation (mm) data for SCRF (Lansing, MI) and SVREC (Richville, MI), 2014–2016.

Site	Year	Apr.	May	June	July	Aug.	Sept.	Total	Apr.–June
					°C				
SCRF	2014	8.0	14.4	20.0	18.8	20.2	15.4	–	–
	2015	8.2	16.3	19.2	20.9	20.3	19.1	–	–
	2016	7.5	14.8	20.3	23.0	22.9	17.4	–	–
	30-yr	8.7	14.7	20.0	22.1	21.3	16.9	–	–
SVREC	2014	7.4	14.3	20.2	19.0	19.7	15.5	–	–
	2015	7.4	15.7	18.5	20.7	20.0	18.6	–	–
	2016	5.6	14.8	19.7	22.6	22.4	18.2	–	–
	30-yr‡	7.7	14.2	19.7	22.1	20.9	16.8	–	–
					mm				–
SCRF	2014	22	83	123	61	86	85	460	Normal§
	2015	23	109	192	61	123	95	604	Excessive
	2016	75	52	18	96	163	106	510	Deficit
	30-yr	73	85	89	83	84	92	505	–
SVREC	2014	101	78	70	106	99	77	531	Normal
	2015	50	73	68	56	100	67	413	Deficit
	2016	33	40	38	88	131	52	382	Deficit
	30-yr‡	81	84	90	79	82	98	513	–

† Air temperature and precipitation data were collected from Michigan Automated Weather Network (http://www.agweather.geo.msu.edu/mawn/) and determined as a mean of the average monthly high and low.

‡ 30-yr mean source for air temperature and precipitation data: National Oceanic and Atmospheric Administration (NOAA) (https://www.ncdc.noaa.gov/cdo-web/datatools/normals).

§ Cumulative April–June rainfall was deemed normal if within 10% above or below 30-yr mean, excessive if above 10%, and deficit if below 10%.

V3 stand counts (data not shown). Corn plant density was 92 to 97% of the targeted planting rate across treatments. In 2014 the IF strategy reduced plant density up to 2.6% relative to other strategies including the untreated control. Dry soil conditions (i.e., 8.9 mm rainfall over 14 d following planting) at the SCRF may have limited diffusion of fertilizer into the soil solution while at the SVREC cool soil temperatures (4.4°C cooler than Lansing with 5 d of consecutive minimums near 7.2°C) may have limited root growth. Either scenario would have increased the amount of time germinating corn roots were exposed to the fertilizer band, which may have resulted in injury (Laboski, 2008). Stand reductions were not observed in other years. Plant density was evaluated as a covariate in the statistical analysis of grain yield, found not significant ($P \leq 0.05$), and was not included in grain yield analysis.

Grain Yield

Grain yield was influenced by the interaction of year, site, and treatment ($P = 0.002$). A significant grain yield response

Table 4. Corn grain yield† as affected by in-furrow (IF), pre-plant incorporated (PPI), and 5×5 N strategies in combination with sidedress timings, at SCRF (Lansing, MI) and SVREC (Richville, MI)‡ 2014–2016.

N strategy	2014 SCRF	2014 SVREC	2015 SCRF	2015 SVREC	2016 SCRF	2016 SVREC
	Mg ha^{-1}					
IF + V4	14.5 ab§	14.0 bc	12.2 bc	12.7 a	12.2 a	13.8 a
IF + V11	13.4 d	13.6 c	12.7 bc	11.4 a	11.8 a	12.4 b
IF + V4/V11	14.4 abc	14.5 ab	13.2 ab	12.4 a	12.0 a	12.9 ab
PPI: urea	13.6 cd	15.0 a	11.9 c	11.2 a	11.8 a	11.2 c
PPI: PCU/urea	13.3 d	14.7 ab	12.0 c	11.5 a	12.4 a	11.1 c
PPI: PL + V11	14.7 a	14.5 ab	13.9 a	12.0 a	12.1 a	13.3 ab
5×5 + V4	13.9 bcd	14.4 abc	12.8 bc	11.9 a	13.1 a	13.0 ab
5×5 + V11	13.4 d	13.7 c	13.1 ab	12.6 a	12.4 a	12.8 b
5×5 + V4/V11	14.2 abc	14.6 ab	12.7 bc	12.3 a	12.7 a	13.3 ab
$P > F$	0.010	0.049	0.046	0.133	0.349	<0.001
Untreated¶	7.2	6.0	5.9	7.2	8.5	5.8
Multiple df contrasts						
IF strategy#	14.1 a	14.0 b	12.7 a	12.1 a	12.0 b	13.0 a
PPI strategy	13.9 a	14.7 a	12.6 a	11.5 b	12.1 b	11.9 b
5×5 strategy	13.8 a	14.2 b	12.9 a	12.3 a	12.7 a	13.0 a
$P > F$	0.633	0.019	0.712	0.065	0.066	0.004
One pass††	13.5 b	14.9 a	11.9 b	11.3 b	12.1 a	11.2 b
Multi-pass	14.1 a	14.2 b	12.9 a	12.2 a	12.3 a	13.0 a
$P > F$	0.035	0.006	0.001	0.011	0.487	<0.001

† Grain yield at 155 g kg^{-1} moisture.

‡ Total maximum return to N rate used at Lansing and Richville locations was 157 and 202 kg N ha^{-1}, respectively, across years.

§ Treatment means within each column followed by the same letter are not significantly different at $P \leq 0.10$.

¶ Untreated control not included in statistical analysis.

Contrasts consisted of three-treatment means that utilized each strategy.

†† One pass system multiple degree of freedom contrast was mean of urea and polymer-coated urea (PCU) and urea treatments. Multi-pass system was a mean of all other treatments combined.

to treatment was observed in 4 of 6 site years and means were presented separately for each site year (Table 4). Mean grain yields for treatments receiving N were 11.8 to 14.7 and 11.1 to 15.0 Mg ha^{-1} at the SCRF and SVREC locations, respectively, with the greatest yields occurring in 2014. In 2 site years (i.e., SVREC 2015 and SCRF 2016), minimal rainfall occurred within 7 d of at-plant N application (0–2.3 mm) and V11 SD (0.3–1.5 mm) and may have reduced mobility of urea-based N fertilizers. These conditions when combined with deficit spring rainfall (i.e., April–June) resulted in dry soils and no response to N placement and timing combinations (Venterea and Coulter, 2015; Maharjan et al., 2016). For the four significant site years, treatments are discussed by near normal to deficit rainfall (i.e., 3 site years) and above normal rainfall (i.e., 1 site year).

When April–June rainfall was normal (i.e., SCRF and SVREC 2014) to deficit (i.e., SVREC 2016) with near-normal air temperatures, no yield gains occurred when full SD was delayed from V4 until V11 (Table 4). Precipitation at SVREC in 2016 coincided with SD applications and provided ≥6.9 mm cumulative rainfall within 3 d of each SD N application likely assisting N movement to corn roots. Delayed N application from V4 to V11 within the IF strategy resulted in similar or 7.6 to 10.1% yield reductions. No statistical differences were observed using the 5×5 strategy with a V4 or V11 SD timing, indicating greater yield consistency across variable weather conditions and concurs with previous research (Ritchie et al., 1996). Similar yields for both the 5×5 V4 and V11 SD strategies emphasizes the importance of starter N for unconstrained early season corn growth. Relative to a split (50:50) application, SD delayed until V11 resulted in similar or 5.6 to 6.9% yield reductions across both the IF and 5×5 strategies, indicating that starter N (8–45 kg N ha^{-1}) was insufficient to reach the V11 growth stage and reduced yield potential. Studies have indicated corn at V11 can sequester approximately 100 kg N ha^{-1}, and thus 45 kg N ha^{-1} provided by the 5×5 strategy from the current study may not have been sufficient to maintain yield potential (Bender et al., 2013). Increased rates of 5×5 fertilizer (i.e., >45 kg N ha^{-1}) may be required when full SD is delayed until V11. Scharf et al. (2002) suggested that a shortened growing season (e.g., northern Corn Belt) may reduce the duration of corn N uptake and may explain full yield potential realization with a V11 SD application in longer growing season climates (e.g., Missouri). Relative to a V4 timing, full SD at V11 was too late to increase yield in near-normal to deficit spring rainfall conditions, and split SD N (50:50) applications did not provide additional yield gains. Results suggest growers who choose to apply SD N beyond V4 should consider application prior to V11 when using IF or 5×5 strategies at the rates in the current study. However, reduced yield potential from the current study suggested the V11 timing may still be considered as a rescue application to achieve yields ≥11.4 Mg ha^{-1} but not used as a standard practice.

In the same site years (i.e., SCRF and SVREC 2014, SVREC 2016), pre-plant incorporated PL followed by V11 SD produced similar yields as IF and V4 SD, indicating yield potential was not increased with a slowly mineralizable N source (60.5 kg N ha^{-1} first year mineralizable N) (Table 4). Poultry litter extended

Table 5. Corn profitability as affected by in-furrow (IF), pre-plant incorporated (PPI), and 5×5 N strategies in combination with sidedress timings, at SCRF (Lansing, MI) and SVREC (Richville, MI)† 2014–2016.

	2014		2015		2016	
N strategy	SCRF	SVREC	SCRF	SVREC	SCRF	SVREC
			Net returns‡ ($ ha^{-1})			
IF + V4	1663 a§	1544 bcd	1412 a	1451 ab	1349 bcd	1521 a
IF + V11	1501 d	1475 d	1470 a	1256 de	1288 d	1329 cde
IF + V4/V11	1618 abc	1570 bc	1514 a	1372 abcd	1300 cd	1369 bcd
PPI: urea	1593 abcd	1719 a	1450 a	1321 bcde	1349 bcd	1244 ef
PPI: PCU/urea	1499 d	1621 b	1395 a	1288 cde	1386 abcd	1167 f
PPI: PL + V11	1558 bcd	1467 d	1498 a	1206 e	1159 e	1276 def
5×5 + V4	1620 abc	1623 b	1550 a	1393 abcd	1505 a	1463 ab
5×5 + V11	1539 cd	1524 cd	1586 a	1484 a	1418 abc	1421 abc
5×5 + V4/V11	1639 ab	1629 ab	1495 a	1416 abc	1435 ab	1464 ab
$P > F$	0.064	0.001	0.376	0.025	0.002	<0.001
Untreated¶	959	798	813	990	1080	741
Multiple df contrasts						
IF strategy#	1595 a	1532 b	1466 a	1360 a	1313 b	1406 a
PPI strategy	1550 a	1602 a	1448 a	1272 b	1298 b	1229 b
5×5 strategy	1599 a	1592 a	1544 a	1431 a	1453 a	1449 a
$P > F$	0.338	0.062	0.145	0.005	0.002	<0.001
One pass††	1546 a	1670 a	1422 a	1305 a	1367 a	1205 b
Multi-pass	1591 a	1548 b	1504 a	1368 a	1351 a	1406 a
$P > F$	0.218	<0.001	0.109	0.152	0.683	<0.001

† Total maximum return to N rate used at Lansing and Richville locations was 157 and 202 kg N ha^{-1}, respectively, in all years.

‡ Net returns calculated as gross return (yield × corn price) minus total costs (N + N protectant + application cost) ha^{-1} per respective year.

§ Treatment means within each column followed by the same letter are not significantly different at $P \le 0.10$.

¶ Untreated control not included in statistical analysis.

Contrasts consisted of three treatment means that utilized each strategy.

†† One pass system multiple degree of freedom contrast was mean of urea and polymer-coated urea (PCU) and urea treatments. Multi-pass system was a mean of all other treatments combined.

N activity relative to other early applied N treatments (i.e., IF or 5×5 strategies) and resulted in similar or increased yields (6.6–9.7%) when full SD was delayed until V11. Increased N rates (i.e., >45 kg N ha^{-1}) provided by a slowly mineralizable N source (i.e., PL) were sufficient to maintain or increase yield (5.8–9.7%) relative to the IF and 5×5 strategies when full SD was delayed until V11. When compared with a urea or PCU and urea blend applied PPI, a PL plus V11 SD application achieved similar or increased yields (8.1–19.8%), respectively, across site years whereas the PCU did not provide yield gains as compared with urea alone. April–June rainfall at SCRF and SVREC in 2014 (normal) and SVREC in 2016 (deficit) may have reduced N loss opportunities and provided no benefit to using PCU.

At SCRF in 2015, excessive May–June rainfall (127 mm excess) resulted in wet soils. In this scenario, pre-plant incorporated PL followed by V11 SD increased yield 8.6 to 13.9% relative to IF or 5×5 starter and V4 SD (Table 4). Moist soil conditions, but a lack of heavy rainfall events in May (<21 mm), may have prevented some degree of early PPI N loss and hindered the effectiveness of PCU. Yield results with PCU contrasted with Gagnon et al. (2012) where corn yield gains (0.8–1.6 Mg ha^{-1}) due to PPI PCU in Canada were observed relative to urea. However, average air temperatures in Lansing, MI, were 5 to 6°C warmer than the Canadian study, which may influence the rate of N release (Franzen, 2017). Although delaying N application until V11 reduced the opportunity for N loss in wet years, this practice did not increase grain yield in other years.

In 5 of 6 site years, multiple df contrasts indicated the IF and 5×5 strategies achieved similar yields (Table 4). Relative to the PPI strategy, when April–June rainfall was deficit (i.e., SVREC 2015 and 2016, SCRF 2016), the 5×5 strategy increased yield 5.0 to 9.2% and illustrated the difficulty associated with PPI N uptake in dry soils. Similar yields were obtained with the IF and 5×5 strategy except at SCRF (2016), where the 5×5 strategy increased yields 5.8%. However, no differences among strategies were observed when May–June rainfall was above normal to excessive (i.e., SCRF 2014 and 2015). Multi-pass N application systems are a university recommended best management practice in Michigan to improve N recovery (Warncke et al., 2009). In 4 of 6 sites years, a multi-pass system increased yields 4.4 to 16.1% relative to a one-pass system. In lieu of variable weather conditions encountered in the current study, yield gains in multi-pass systems suggest improved synchrony of N application with corn uptake. Increased starter N rates with the 5×5 strategy may offer greater yield consistency from increased N supply at V6 when compared with low N rates applied IF.

Profitability

Profitability was influenced by the interaction of year, site, and treatment ($P = 0.001$). Treatment means were presented separately by site and year (Table 5). Across years, grain yield was directly proportional with profitability ($r \ge 0.82$, $P < 0.01$) and inversely proportional with total treatment cost ($r \le -0.29$, $P \ge 0.01$). An inverse relationship with total treatment costs suggested growers should consider N and application costs in addition to yield when maximizing profitability.

Full SD N applied at V11 did not increase profitability (Table 5). When cumulative April–June rainfall was near normal to deficit (i.e., SCRF and SVREC 2014, SVREC 2016), SD delayed from V4 to V11 with the IF strategy produced similar or reduced profitability (192–195 \$ ha^{-1}) (3 of 6 site years). A similar reduction in profit was observed (\$99 ha^{-1}) (1 of 6 site years) with the 5×5 strategy (i.e., SVREC 2014). The reduced frequency of profit loss with the 5×5 strategy stabilized profit variability among SD timings. Increased at plant N rates with the 5×5 strategy may allow greater SD timing flexibility when deliberating from a V4 through V11 SD application. Despite similar yields, split-applied SD (50:50) resulted in similar or reduced (\$152 ha^{-1}) profitability relative to IF or 5×5 starter with full V4 SD, suggesting no improved profit from a second SD application. When cumulative April–June rainfall was normal (i.e., SCRF and SVREC 2014), a full V11 SD application reduced profitability relative to both split-applied SD with starter IF (\$95–\$117 ha^{-1}) and 5×5 (\$100–\$105 ha^{-1}). Although similar profits were often achieved with IF and 5×5 plus V4 SD, growers wanting to utilize a V11 SD application appear more likely to maintain profitability utilizing the 5×5 strategy.

In the same site years (i.e., SCRF and SVREC 2014, SVREC 2016), a PL and V11 SD application resulted in comparable or reduced profitability (\$154–\$252 ha^{-1}) relative to PPI urea or PCU and urea (Table 5). Likewise, PCU and urea resulted in similar or reduced profitability (\$98 ha^{-1}) relative to a urea PPI application. Reduced profitability and increased PCU N costs (\$0.42–\$0.54 kg^{-1} N) relative to urea N emphasizes the risk associated with using enhanced efficiency N fertilizers without N loss conditions (i.e., SVREC 2014). Profitability with a single V11 SD application was most affected in dry spring seasons (i.e., SVREC 2015 and 2016, SCRF 2016) and emphasized the importance of considering N costs when deliberating N strategies. For instance, despite similar yield, PL+V11 SD occasionally reduced profitability relative to full V11 SD following IF (\$129 ha^{-1}) and 5×5 strategies (\$145–\$278 ha^{-1}). At the same time, a 5×5 strategy with V11 SD increased profitability (\$130–\$228 ha^{-1}) relative to the IF application (2 of 6 site years) and illustrated the ability of an additional 37 kg N ha^{-1} applied at planting in a 5×5 to increase profits compared with 8 kg N ha^{-1} applied IF. In dry years a PL with V11 SD reduced profitability relative to a V4 SD with IF (\$190–\$245 ha^{-1}) or 5×5 strategy (\$186–\$346 ha^{-1}) with fewer apparent differences during normal rainfall. The PL-N source cost up to 5.7 times greater than urea-N and UAN-N sources, which further emphasized consideration for N source costs rather than yield individually. Despite greater grain yield in a wet year, similar profits with PL and V11 SD compared with IF or 5×5 starter with V4 SD indicated N savings due to improved synchrony of N application, and uptake was not sufficient to offset the increased cost of the PL treatment.

Profitability between IF, PPI, and 5×5 strategies corresponded to yield data as indicated by multiple df contrasts. When April–June rainfall was near-normal to excessive (i.e., SCRF and SVREC 2014, SVREC 2016), strategies often resulted in similar profitability (Table 5). However, under deficit April–June rainfall conditions, PPI profitability was reduced relative to the 5×5 (\$155–\$220 ha^{-1}) and IF strategies (\$88–\$177 ha^{-1}) and illustrated the difficulty associated with PPI N uptake, grain production, and subsequent profitability in dry soils. In two instances an IF strategy reduced profitability (\$60–\$140 ha^{-1}) as compared to the 5×5 strategy. In 4 of 6 site years no differences were observed between one and multi-pass N application systems, indicating weather variability impacted profitability less than yield. In two contrasting years, reduced N loss opportunities increased profitability of a one-pass system (\$122 ha^{-1}), whereas reduced PPI N uptake in dry soils reduced profitability (\$201 ha^{-1}) relative to the multi-pass system. Growers often perceive yield loss as a larger risk than profit loss. One-pass systems increased the frequency of yield loss whereas a 5×5 strategy achieved similar or increased profitability relative to other strategies. Results suggest a multi-pass system with a 5×5 strategy may reduce risk of profit loss when weather variability influences yield.

Plant Characteristics

Normalized Difference Vegetation Index

Pearson correlations indicated significant relationships between V6 NDVI and yield across years at Lansing ($r = 0.42$, $P < 0.01$) and Richville ($r = 0.76$, $P < 0.01$) and were similar to an r value of 0.46 used to predict grain yield with V8 NDVI in another study (Liu and Wiatrak, 2011). In the current study, positive relationships suggested corn yield increases in relation to NDVI and emphasized the importance of N management strategies to sufficiently supply N to maintain yield potential until SD time.

Active V6 canopy sensing indicated a significant year × treatment ($P = 0.037$) and location × treatment ($P < 0.001$) interaction. Multiple df contrasts were constructed and presented separately for year and location (Table 6). The NDVI is an indicator of green biomass and has been used to compare plant growth response and N management (Tucker, 1979). When cumulative April–June rainfall was deficit at both sites (i.e., 2016), multiple df contrasts were not significant and suggested that deficit rainfall reduced corn growth response to N strategies. The NDVI increased with PPI or IF N strategies relative to a 5×5 N placement and suggested increased positional N availability when soils were not dry (i.e., 2015 and SCRF). Compared with corn receiving no N (i.e., untreated), the IF, 5×5, and PPI N increased corn NDVI (7.8–19.2%). Increased NDVI in corn receiving N at planting suggested native soil N supplies were insufficient to achieve similar growth in unfertilized corn. Corn requires nearly 15% of the total N uptake by V6, which may be supplied by soil N mineralization (Bender et al., 2013). Although corn yield potential is determined prior to V8, N deficiencies 10 to 42 d after emergence have decreased stem elongation, leaf area, and net photosynthetic rate resulting in less dry matter accumulation and reduced yield potential, further emphasizing the importance to supply sufficient N early in the growing season when photosynthetic rates are high (i.e., μmol CO_2 m^{-2} s^{-1}) (Varvel et al., 1997; Binder et al., 2000; Zhao et al., 2003; Yu et al., 2016).

Active canopy sensing at V11 SD application was not influenced by interaction of site ($P = 0.122$) or year ($P = 0.870$) and data were presented by treatment (Table 7). Pearson correlations indicated a significant relationship between V11 NDVI and yield across years and locations ($r = 0.37$, $P < 0.001$) for treatments receiving a V11 SD application. A significant relationship indicated that early N management (i.e., IF, 5×5, PL PPI) affected yield response to the V11 timing, which may be

Table 6. Multiple degree of freedom contrasts used to compare V6† normalized difference vegetation index (NDVI) as affected by in-furrow (IF), pre-plant incorporated (PPI), and 5×5 N strategies combined across SCRF (Lansing, MI) and SVREC (Richville, MI) locations in 2014, 2015, 2016, and combined across years at each location.

	Years			Locations	
N strategy	2014	2015	2016	SCRF	SVREC
			NDVI		
IF starter only‡	0.47 b§	0.40 a	0.32 a	0.46 a	0.32 b
PPI strategy¶	0.50 a	0.38 a	0.32 a	0.45 a	0.35 a
5×5 starter only	0.46 b	0.35 b	0.31 a	0.41 b	0.34 ab
Untreated control	0.43 c	0.34 b	0.31 a	0.42 b	0.29 c
$P > F$	<0.001	<0.001	0.856	0.001	<0.001

† Not all treatments at V6 have received total seasonal N application (i.e., V11 N applications).

‡ The IF and 5×5 strategies indicated as "starter" as these contrasts only contained those treatments not receiving SD N to enable comparison with PPI N and the untreated control.

§ Treatment means within each column followed by the same letter are not significantly different at $P \leq 0.10$.

¶ Strategy indicates a mean of all three treatments utilizing the PPI strategy.

Table 7. Mean V11 normalized difference vegetation index (NDVI) and multiple degree of freedom NDVI contrasts as affected by in-furrow (IF), pre-plant incorporated (PPI), and 5×5 N strategies in combination with sidedress timings, across locations and years† in Lansing and Richville, MI, 2015–2016.

N strategy	NDVI
IF + V4	0.7309 a§
IF + V11‡	0.6823 d
IF + V4/V11	0.7223 ab
PPI: urea	0.7071 bc
PPI: PCU/urea	0.7157 abc
PPI: PL + V11	0.7274 ab
5×5 + V4	0.7132 abc
5×5 + V11	0.7003 cd
5×5 + V4/V11	0.7190 abc
$P > F$	0.050
Untreated¶	0.6526
Multiple df contrasts	
IF starter only#	0.6823 b
PPI strategy††	0.7168 a
5×5 starter only	0.7003 ab
Untreated control	0.6526 c
$P > F$	<0.001

† Data were not collected in 2014.

‡ Not all treatments at V11 have received total seasonal N application (i.e., V11 N applications).

§ Treatment means followed by the same letter are not significantly different at $P \leq 0.10$.

¶ Untreated not included in analysis of pairwise comparisons.

The IF and 5×5 strategies indicated as "starter" as these contrasts only contained those treatments not receiving SD N to enable comparison with PPI N and the untreated control.

†† Strategy indicates a mean of all three treatments utilizing the PPI strategy.

useful in future studies where canopy sensing is used to adjust in-season N rates. When full SD rates were delayed from V4 to V11, the IF strategy reduced NDVI 6.6% as compared with a 1.8% reduction with the 5×5 strategy. The larger NDVI reduction with the IF strategy indicated that the 8 kg N ha^{-1} was not sufficient to supply the required N for both green biomass and chlorophyll production and suggested less potential to capture photosynthetically active radiation (PAR) (Zhao et al., 2003). However, the PL application, which had not yet received V11 SD, increased NDVI (3.9–6.6%) relative to the IF and 5×5 strategies across all site years and suggested increased potential to maintain yield until the V11 SD timing. All strategies increased V11 NDVI relative to unfertilized corn. Increased NDVI in corn receiving PPI N (5.1%) relative to IF N but not 5×5 N suggested N rates >8 kg N ha^{-1} were required to improve NDVI. However, N rates >8 kg N ha^{-1} may negate the use of the IF strategy due to reduced stand density via saltation.

Chlorophyll Content

Chlorophyll meter values were influenced by the interaction of year, site, and treatment and data were presented by treatment for each site year (Table 8). Except for a wet year (i.e., SCRF 2015), relative CM indices indicated reduced plant chlorophyll when SD was delayed from V4 to V11 within both the IF (2.0–22%) and 5×5 (4.1–9.2%) strategies. Decreased chlorophyll reduced photosynthesis for corn grain production (Hatfield and Parkin, 2014; Yu et al., 2016). Reduced CM values when delaying SD from V4 to V11 indicated less N was sequestered and assimilated into canopy tissues for photosynthesis and corresponded to yield reductions. Delaying full SD N from V4 to V11 (i.e., IF or 5×5) may be too late to achieve similar chlorophyll levels and suggests corn may not have sufficient time to fulfill N uptake requirements. When May–June rainfall was below normal (i.e., SVREC 2014–2016, SCRF 2016), PL with V11 SD often reduced CM values relative to IF or 5×5 starter and V4 SD (5–10%) and other PPIs (4.3–6.3%) likely due to reduced moisture required for mineralization. In the same years, PL and IF strategies receiving V11 SD resulted in CM values below criterion previously used to trigger N application in Michigan (≤0.96) and indicated N stress (Elwadie et al., 2005). However, studies indicate that 35% of total corn N uptake occurs post-silking in modern hybrids (Bender et al., 2013). Despite CM values below a 0.96 threshold, statistically higher grain yields in all years with PL applications suggested that a slowly mineralizable N source may continue to provide sufficient N for uptake and assimilation during corn reproductive stages (Bender et al., 2013). Across treatment strategies and one- vs. multi-pass application systems, multiple df contrasts indicated CM values were generally ≥0.96 with few biologically significant differences. To maintain chlorophyll production, data suggest increased N rates (>45 kg N ha^{-1}) may be required at planting if SD is delayed until V11.

CONCLUSIONS

With near-normal to deficit rainfall (i.e., April–June), delaying full SD from V4 to V11 did not increase yield. The IF strategy resulted in similar or 7.6 to 10.1% reduced yield and $192 to $195 ha^{-1} lower profitability when SD was delayed from V4 to V11. The 5×5 strategy resulted in no yield differences and reduced profitability in only 1 of 6 site years with delayed SD N application. Greater starter N rates afforded by the 5×5 strategy may stabilize both profit and yield variability. Regardless of 5×5 or IF strategy, similar or 5.6 to 6.9% reduced yields with delayed V11 SD relative to a 50:50 split SD indicated that starter N (8–45 kg N ha^{-1}) may have been insufficient, while reduced

Table 8. Mean R1 relative† chlorophyll (CM) meter measurements as affected by in-furrow (IF), pre-plant incorporated (PPI), and 5×5 N strategies in combination with sidedress timings, at SCRF (Lansing, MI) and SVREC (Richville, MI)‡, 2014–2016.

	2014		2015		2016	
N strategy	SCRF	SVREC	SCRF	SVREC	SCRF	SVREC
			Relative CM index			
IF + V4	0.99 a§	0.97 cd	0.95 bc	1.00 a	1.00 a	1.04 a
IF + V11	0.97 bcd	0.91 e	0.94 c	0.78 e	0.92 d	1.00 bc
IF + V4/V11	0.99 abc	1.02 ab	0.99 a	0.97 ab	1.00 a	1.01 abc
PPI: urea	0.99 abc	1.00 abc	0.98 ab	0.96 bc	0.98 abc	0.99 c
PPI: PCU/urea	0.96 d	1.00 bc	0.95 bc	0.94 c	1.00 a	1.00 bc
PPI: PL + V11	0.99 ab	0.95 d	0.99 a	0.90 d	0.95 c	0.95 d
5×5 + V4	0.97 cd	1.03 a	0.99 a	0.98 ab	1.01 a	1.02 ab
5×5 + V11	0.93 e	0.97 d	0.98 a	0.89 d	0.96 bc	0.99 bc
5×5 + V4/V11	0.97 abcd	1.01 abc	0.99 a	0.97 abc	0.99 ab	1.03 a
$P > F$	0.052	<0.001	0.019	<0.001	<0.001	<0.001
Untreated¶	0.74	0.71	0.72	0.74	0.84	0.73
Multiple df contrasts						
IF strategy#	0.98 a	0.97 b	0.96 a	0.92 b	0.97 a	1.02 a
PPI strategy	0.98 a	0.98 ab	0.97 a	0.93 ab	0.98 a	0.98 b
5×5 strategy	0.96 b	1.00 a	0.99 a	0.95 a	0.98 a	1.01 a
$P > F$	0.013	0.074	0.119	0.078	0.523	<0.001
One pass††	0.97 a	1.00 a	0.96 a	0.95 a	0.99 a	0.99 a
Multi-pass	0.97 a	0.98 a	0.97 a	0.93 b	0.97 a	1.00 a
$P > F$	0.818	0.124	0.410	0.074	0.129	0.135

† Readings normalized to non-limiting N control (280 kg N ha^{-1}).

‡ Total maximum return to N rate used at Lansing and Richville locations was 157 and 202 kg N ha^{-1}, respectively, in all years.

§ Treatment means within each column followed by the same letter are not significantly different at $P \leq 0.10$.

¶ Untreated control not included in statistical analysis.

Contrasts consisted of 3-treatment means that utilized each strategy.

†† One pass system multiple degree of freedom contrast was mean of urea and PCU and urea treatments. Multi-pass system was a mean of all other treatments combined.

profitability also indicated no benefit to a second SD application. Increased N rates (>45 kg N ha^{-1}) may be required when waiting to apply full SD at V11. Poultry litter did not increase yield potential relative to other strategies (i.e., IF or 5×5 plus V4 SD), but when full SD was delayed until V11 6.9 to 9.7% increased yields from PL application were offset by the increased N cost, which reduced profitability \$129 to \$278 ha^{-1}. Blending urea with PCU did not affect yield in relation to 100% urea and reduced profitability \$98 ha^{-1}, emphasizing the risk of enhanced efficiency N use without N loss conditions. In wet spring soils, PL followed by V11 SD increased yield 8.6 to 13.9% relative to either the IF or 5×5 strategies with V4 SD.

Multi-pass N application systems increased yield 4.4 to 16.1% relative to one-pass systems in 4 of 6 site years, suggesting improved N synchrony with corn N uptake. Delaying bulk N applications until V11 may have reduced the opportunity for N loss in wet years, but this practice did not increase the opportunity for yield gains in other years. Because SD N applications are often dependent on seasonal weather patterns, growers must leverage risk when deliberating between V4 and V11 SD. When using the IF or 5×5 strategies at the N rates in this study, sidedress N post-V4 should occur before a V11 timing. The ability of any strategy to sufficiently supply N until SD is critical to maintaining yield potential. Canopy sensory data suggested the IF, PPI, and 5×5 strategies increased plant vigor at V6 and V11 relative to an unfertilized control, but reduced N rates required by the IF strategy may reduce the capacity to maintain yield potential when full SD is delayed from V4 to V11. Weather forecast models can vary in their predictive accuracy, and reduced yield potential and economic response to V11 SD N suggested less risk was associated with the V4 timing. However, growers missing the V4 application window may utilize the V11 timing as a rescue application to achieve yields ≥11.2 Mg ha^{-1}. Growers utilizing a rescue application are more likely to maintain yield and profitability if preceded by increased N rates in the 5×5 strategy.

As models predict warmer temperatures, the use of relative maturity class corn hybrids greater than 98 d during a lengthened growing season may create greater opportunities for late-season N applications to have a significant impact on grain yield in northern climates. Future studies that include similar treatments and multiple corn hybrids replicated across Corn Belt regimes may provide evidence to substantiate this idea as well as additional data and tools to address N management in a changing 21st century climate.

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