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Comparing nitrogen timing and sidedressing placement strategies on corn growth and yield in Michigan

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Abstract

Spring and summer weather volatility plus poor N use efficiency emphasize the importance of improving corn (*Zea mays* L.) N management strategies. Synchronizing N application with crop uptake and flexibility for in-season sidedressing placement options may reduce N losses. Field studies in Michigan evaluated four N timing strategies: broadcast pre-emergence (PRE), sidedressing at V4 to V6 (0:100), a 50:50 split between preplanting incorporation and sidedressing at V4 to V6 (50:50), and 40 lb N acre^{-1} applied 2 inches below and laterally from the seed at planting followed by sidedressing at V4 to V6 (2 × 2). Within the 0:100, 50:50, and 2 × 2 strategies, the two sidedressing placement methods included coulter injection (CInj) and Y-drop surface application (YD). The PRE N strategy and YD placement were applied with and without a urease inhibitor (UI). During dry soil conditions following application, N timing, sidedressing placement, and their combinations did not affect grain yield. The agronomic efficiency (AE) of applied N increased by 11.2 to 13.5% with 2 × 2 and 0:100 compared with 50:50 and PRE and increased by 7.8% with CInj over YD, suggesting greater application efficiency with delayed N application and CInj placement. Grain yield, net economic return, and AE were not affected by UI. Midseason N applications allow greater flexibility and adjustments to rate and placement but uptake may be restricted with limited soil moisture. The benefits of YD surface placement may be better realized with adequate surface moisture or as late-season rescue N applications.

1 | USING NITROGEN TIMING AND PLACEMENT TO IMPROVE CORN YIELD

Reductions in both ground and surface water quality have driven the continued interest in improving corn N management strategies (Schepers, Moravek, Alberts, & Frank, 1991; Smil, 1997). Since 2008, mean United States (U.S.) corn grain yields have increased by 25 bu acre^{-1},yet N use efficiencies of 33 to 47% indicate that the applied N is not recovered by the plant (Lassaletta, Billen, Grizzetti,

Abbreviations: 0:100, 100% of N applied as sidedressing at V4 to V6; 2 × 2, subsurface N application 2 inches below and laterally from the seed; 50:50, 50% of N incorporated before planting with 50% of N applied as sidedressing at V4 to V6; AE, agronomic efficiency; CInj, coulter injection; CM, chlorophyll meter; *N*-(*n*-butyl) thiophosphoric triamide, NBPT; NDVI, normalized difference vegetation index; PPI, preplanting incorporation; PRE, pre-emergence; UAN, urea ammonium nitrate; UI, urease inhibitor; YD, Y-drop application.

TABLE A1 Useful conversions

To convert Column 1 to Column 2, multiply by	Column 1 suggested unit	Column 2 SI unit
9.35	gallon per acre, gal/acre	liter per hectare, L/ha
0.304	foot, ft	meter, m
62.71	56-lb bushel per acre, bu/acre	kilogram per hectare, kg/ha

Core Ideas

- The N timing and placement did not influence grain yield N response in dry conditions.
- Delayed N application may allow placement and rate flexibility, but moisture is needed.
- Surface N may have more potential for positional unavailability in dry conditions.
- V4–V6 application and coulter-injected sidedressed N may improve agronomic efficiency.
- Positive relationships between grain yield and R4 chlorophyll meter values indicated greater plant N status and chlorophyll production translated into increased grain yield.

Anglade, & Garnier, 2014; Raun & Johnson, 1999; Rubin, Struffert, Fernández, & Lamb, 2016; USDA-NASS, 2018). Climatic variability, including more frequent and longer periods of drought followed by intense rainfall, combined with N application outside of peak uptake periods may increase the potential for N loss (Cassman, Dobermann, & Walters, 2002; Karl, Melillo, & Peterson, 2009; Schepers et al., 1991; Smil, 1997; Venterea & Coulter, 2015). Environmental variables (i.e. precipitation and soil moisture) influence N availability and mobility within the soil; therefore, greater emphasis has been placed on decreasing N losses through optimal placement and timing strategies (Bock, 1984; Bruulsema, Lemunyon, & Herz, 2009; Gardinier, Ketterings, Verbeten, & Hunter, 2013).

As farm size increases, PRE N applications (i.e., broadcast-applied N after planting but prior to crop emergence) have been used to reduce the time and labor resource requirements of multiple-pass systems by combining weed control and fertilization into a single-pass application (Fox & Piekielek, 1993). Although PRE N strategies can be as effective as other N application methods, the potential for N loss may increase through volatilization of surface-applied urea-containing N sources [e.g., urea and urea ammonium nitrate (UAN)] (Lehrsch, Sojka, & Westermann, 2000; Nelson, Scharf, Stevens, & Burdick, 2011; Randall, Iragavarapu, & Bock, 1997; Stecker, Buchholz, Hanson, Wollenhaupt, & McVay, 1993). Incorporating surface-applied N is a recommended Michigan practice and may reduce the risk of N loss and protect economic investments related to weather volatility (Warncke, Dahl, & Jacobs, 2009). However, N mobility and availability from preplanting incorporation (PPI) may be limited under dry soil conditions and reduce early-season growth relative to starter fertilizer placed 2 inches below and 2 inches to the side of the seed (the 2 × 2 treatment) (i.e. subsurface N placement) (Chaidhary & Prihar, 1974; Khosla, Alley, & Davis, 2000; Rutan & Steinke, 2018). In Michigan, Rutan and Steinke (2018) reported that PPI application reduced yield relative to subsurface N placement when deficit cumulative April to June rainfall occurred but resulted in similar yields when cumulative May to June precipitation was above normal. Despite flexibility in the N rate with 2 × 2 applications compared with in-furrow starter N, 20 to 40 lb N acre^{-1} is recommended in the North Central United States, followed by sidedressing applications to improve N recovery and reduce N loss potential (Niehues, Lamond, Godsey, & Olsen, 2004; Vitosh, Johnson, & Mengel, 1995; Warncke et al., 2009).

Sidedressing N during corn growth is one method growers use to improve the synchrony of N application with corn's uptake (Rutan & Steinke, 2018). The timing of sidedressing applications may depend on the ability of early-N management strategies to maintain corn's yield potential until the preferred sidedressing time (Rutan & Steinke, 2018). Delaying N application until later in the season (i.e., V10) may reduce corn yield potential, whereas N applications made prior to peak uptake periods are exposed to a greater risk of N loss (Scharf, Wiebold, & Lory, 2002; Walsh, Raun, Klatt, & Solie, 2012). In Nebraska, Russelle, Hauck, and Olson (1983) reported no yield reductions when N applications were delayed until V8 and V16. Similar results were reported in Missouri, where no yield reductions were observed when delaying sidedressed N applications until V11 (Scharf et al., 2002). However, a recent study reported little to no benefit in delaying sidedressed N applications from V4 to V11 under dry conditions or when applying less than 40 lb N acre^{-1} at planting as a starter N application (Rutan & Steinke, 2018). Supplying the majority of N near the beginning of rapid uptake (i.e., V6–V8) may reduce the risk of N loss while maintaining corn yield potential (Bender, Haegele, Ruffo, & Below, 2013; Scharf et al., 2002).

Warm, moist soil conditions during June and July can increase the risk of volatile N loss, but CInj of sidedressed N at 4 to 5 inches deep halfway between corn rows may reduce volatile N losses (Fox, Kern, & Piekielek, 1986; Warncke et al., 2009). Woodley et al. (2018) reported an average yield decrease of 11% when UAN was surface-streamed compared with coulter-injected UAN in Ontario. Similar results were reported by Stecker et al. (1993), where coulter-injected UAN increased corn yield by 5 to 40% relative to surface broadcast UAN and 4 to 20% relative to surface-banded UAN between rows. Root density is greater near the base of a corn plant and decreases with distance from the plant (Anderson, 1987; Ordóñez et al., 2018). A study in Oklahoma evaluating surface N placement 0 to 12 inches from the row found no differences in grain yield or N use efficiency across placement distances (Rutto, Vossenkemper, Kelly, Chim, & Raun, 2013). Mueller et al. (2017) reported increased N recovery and efficiency with surface-band N application adjacent to the base of the plant at the V12 stage relative to coulter-injected N at V3, although no differences in grain yield occurred. Studies evaluating surface N placement adjacent to the plant relative to Cinj at the same growth stage individually and as a component within other N timing strategies are minimal and warrant further investigation.

Volatile N losses increase with increasing soil pH, surface residue, air and soil temperature, and precipitation-free periods (Fox et al., 1986; Franzen, 2017; Schwab & Murdock, 2010; Stecker et al., 1993). The addition of a UI to urea-containing N sources has been used to reduce NH_3 volatilization (Pan, Lam, Mosier, Luo, & Chen, 2016). Urease inhibitors reduce the rate at which urea is hydrolyzed by the urease enzyme for up to 10 d (Franzen, 2017). In a global synthesis on ammonia volatilization, Pan et al. (2016) suggested that UIs reduced volatilization by up to 54%. In Pennsylvania, fertilizer use efficiency, N uptake, and corn grain yield were improved when PRE applications were combined with a UI [*N*-(*n*-butyl) thiophosphoric triamide (NBPT) and ammonia losses reduced by up to 29% (Fox & Piekielek, 1993). When NBPT-coated urea was used in Missouri, Nelson et al. (2011) observed a corn grain yield increase of 4.1 bu $acre^{-1}$ across multiple N application timings. However, the uncharged urea molecule may be prone to leaching when treated with a UI (Dawar, Zaman, Rowarth, Blennerhassett, & Turnbull, 2011; Quinn & Steinke, 2019). Environmental conditions promoting NH_3 volatilization need to be present to observe a positive yield response from a UI (Woodley et al., 2018). The use of a UI may be considered a risk management tool for which growers may not always realize a yield benefit (Quinn & Steinke, 2019).

Poor plant N recovery and utilization for grain production (i.e., AE) coupled with decreasing commodity prices (i.e., a reduction of \$0.24 bu^{-1} since 2015) and unpredictable weather patterns emphasize the importance of considering the economic returns of N management strategies (USDA-NASS, 2020; Walsh et al., 2012). The AE of applied N can be influenced by nutrient deficiencies, hybrid, tillage system, crop rotation, irrigation, and pest pressure but largely depend on environmental conditions and soil moisture (Attia, Shapiro, Kranz, Mamo, & Mainz, 2015; Fixen & West, 2002; Warncke et al., 2009; Woli et al., 2016). Nitrogen placement and application timing may influence synchronization with weather patterns, influencing N loss and therefore affecting AE and net farm profit (Bruulsema et al., 2009). The objective of this study was to evaluate the effects of multiple N timing and sidedressing placement strategies on corn growth, grain yield, the AE of applied N, and net economic return.

2 | LOCATIONS AND SITE DESCRIPTIONS

Field trials were conducted from 2017 to 2018 at the Saginaw Valley Research and Extension Center in Richville, MI, (43°23′57.3″N, 83°41′49.7″W) on a nonirrigated Tappan–Londo loam soil (Tappan: fine-loamy, mixed, active, calcareous, mesic Typic Epiaquolls; Londo: fine-loamy, mixed, semiactive, mesic Aeric Glossaqualfs) and at the South Campus Research Farm in Lansing, MI, (42°42′37.0″N, 84°28′14.6″W) on a nonirrigated Capac loam soil (fine-loamy, mixed, active, mesic Aquic Glossudalf). The Richville locations were previously cropped to winter wheat (*Triticum aestivum* L.); the Lansing locations were previously cropped to soybean [*Glycine max* (L.) Merr.]. Tillage included autumn chisel plowing (8 inch) and spring field cultivation (4 inch). Preplanting soil characteristics at Richville were 7.2 to 7.8 pH (1:1 soil/water) (Peters, Nathan, & Laboski, 2015), 2.3 to 2.8% soil organic matter (loss on ignition) (Combs & Nathan, 2015), 23 to 27 ppm P (Bray-P1) (Frank, Beegle, & Denning, 2015), and 108 to 173 ppm K (ammonium acetate method) (Warncke & Brown, 2015). Soil characteristics at Lansing were 7.1 to 7.9 pH, 2.8 to 3.1% soil organic matter, 13 to 14 ppm P, and 82 to 196 ppm K. Broadcast P and K fertilizer were applied as triple-superphosphate (0–45–0 N–P_2O_5–K_2O) and muriate of potash (0–0–62 N–P–K) in line with soil tests. Prior to planting, soil nitrate-N (NO_3^-) samples were collected (12 inch), air-dried, and ground to pass through a 0.08-inch sieve, resulting in concentrations between 3.5 to 5.7 ppm NO_3^- (nitrate electrode method) across years and locations (Gelderman and Beegle, 2015). Weed control consisted of S-metolachlor[2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-([2S]1-methoxypropan-2-yl)acetamide] and glyphosate [2-(phosphonomethylamino)acetic acid] followed by a second application of glyphosate at both locations across years. Cumulative growing season

TABLE 1 Overview of corn N timing and sidedressing placement strategies at Richville and Lansing, MI, in 2017 at 2018

Treatment	N rate[a]	N strategy[b]
	lb N acre^{-1}	
1	0	Untreated control
2	170, 145	PRE
3	170, 145	PRE + UI[c]
4	170, 145	50:50, PPI–SDr CInj
5	170, 145	50:50, PPI–SDr YD
6	170, 145	50:50, PPI–SDr YD + UI[d]
7	170, 145	0:100, PPI–SDr CInj
8	170, 145	0:100, PPI–SDr YD
9	170, 145	0:100, PPI–SDr YD + UI[d]
10	170, 145	2 × 2, 40 lb N acre^{-1} 2 × 2–remainder of N SDr CInj
11	170, 145	2 × 2, 40 lb N acre^{-1} 2 × 2–remainder of N SDr YD
12	170, 145	2 × 2, 40 lb N acre^{-1} 2 × 2–remainder of N SDr YD + UI[d]

[a]The maximum return to N rate used in Richville and Lansing was 170 and 145 lb N acre^{-1}, respectively.
[b]PRE, pre-emergence N application; UI, urease inhibitor; SDr, sidedressing; PPI, preplanting incorporation; 50:50, 50% of N incorporated before planting and 50% of N applied at V4 to V6 as sidedressing; 0:100, 100% of N applied at V4 to V6 sidedressing; 2 × 2, subsurface N application 2 inches below and laterally from the seed; CInj, coulter injection; YD, Y-drop surface application.
[c]Urease inhibitor [*N*-(*n*-butyl)-thiophosphoric triamide; NBPT] applied at a rate of 2.0 qt ton^{-1} urea.
[d]Urease inhibitor (NBPT) applied at a rate of 1.0 qt ton^{-1} urea ammonium nitrate.

weather data were collected from Michigan State University Enviroweather (https://enviroweather.msu.edu, accessed 11 June 2020). The 30-yr means for monthly air temperature and cumulative precipitation were obtained from NOAA (NOAA, 2018).

3 | EXPERIMENTAL PROCEDURES FOR N TIMING AND PLACEMENT

Trials consisted of 12 treatments arranged in a randomized complete block design with four replications. Treatments included 11 N strategies and a zero-N control (Table 1). Four N timing strategies were used and included: (1) N applied immediately after planting (PRE) (Treatments 2–3, Table 1), (2) 50% of N via PPI with 50% of N as sidedressing (50:50) (Treatments 4–6), (3) all N applied as sidedressing (0:100) (Treatments 7–9), and (4) 40 lb N acre^{-1} applied 2 inches below and to the side of the seed with the remaining N as sidedressing (2 × 2) (Treatments 10–12). The PRE strategy included one treatment with and one without a NBPT UI (Agrotain Advanced, Koch Agronomic Services LLC, Wichita, KS) at 2.0 qts ton^{-1} urea. Treatment combinations within the 50:50, 0:100, and 2 × 2 strategies included evaluations of the following sidedressing methods: (1) CInj at 4 inches deep and 15 inches from the plant, (2) YD (360 Yield Center, Morton, IL) surface-applied on both sides at the base of the plant, and (3) YD with a NBPT UI (Agrotain Advanced) at 1.0 qt ton^{-1} UAN. Sidedressing applications occurred at V4 to V6 on 6 June 2017 and 31 May 2018 in Richville and on 9 June 2017 and 7 June 2018 in Lansing. The N source for the PRE and PPI applications consisted of urea (46–0–0 N–P–K), whereas the 2 × 2 and sidedressing applications were applied as UAN (28–0–0 N–P–K). Nitrogen rates were equalized to a total N rate on the basis of the site-specific maximum return to N rate resulting in 170 lb N acre^{-1} in Richville and 145 lb N acre^{-1} in Lansing (Sawyer et al., 2006). Plots measured 15 ft in width and 40 ft in length and used Dekalb DKC51-38 (Monsanto Co., St. Louis, MO) seeded in 30-inch rows at 34,500 seeds acre^{-1} with a Monosem planter (Monosem Inc., Kansas City, KS) on 28 Apr. 2017 and 1 May 2018 in Richville and 12 May 2017 and 8 May 2018 in Lansing.

Canopy normalized difference vegetation index (NDVI) was collected at V6 and V10 with a handheld red-band optical sensor (GreenSeeker Model 505, Trimble Agriculture Division, Westminister, CO). Corn ear leaf N status at R1 and R4 were assessed with a Minolta SPAD 502 chlorophyll meter (CM) (Konica Minolta, Tokyo, Japan). Ten plants were randomly selected in each plot with one measurement per plant recorded from halfway between the leaf collar and leaf tip (Peterson, Blackmer, Francis, & Schepers, 1993). The center two rows (5 ft wide) of each plot were harvested with a Massey Ferguson 8XP research combine (Kincaid Equipment Manufacturing, Haven, KS) to determine grain yield, moisture, and test weight. Yield data were reported at 15.5% moisture. Agronomic efficiency was calculated as the difference between the yield of treatments with N and the yield of unfertilized control, divided by the N rate (Sawyer, Woli, Barker, & Pantoja, 2017). Net economic return was calculated as the product of grain price and yield minus the total input cost for each treatment. The sum of fertilizer, chemical, and application costs equaled total input costs. Average grain prices from three local grain elevators (ADM Grain Co, Grand Ledge, MI; Michigan Agricultural Commodities, Middleton, MI; and Star of the West Milling Co, Richville, MI) were of \$3.49 bu^{-1} in 2017 and \$3.67 bu^{-1} in 2018 (Table 2). Fertilizer and UI prices from three local retailers (Nutrien Ag Solutions, Henderson, MI; Wilbur-Ellis, Three Rivers, MI; and

TABLE 2 Input costs[a] and prices received[b] used for economic analysis, 2017 and 2018

Variable	Product	2017	2018
	Costs	——$ ton^{-1}——	
Fertilizer[c]	Urea ammonium nitrate (28–0–0 N–P–K)	183	229
	Urea (46–0–0 N–P–K)	305	360
Urease Inhibitor	Agrotain Advanced	——$ gallon^{-1}——	
		130	130
Application costs		——$ acre^{-1}——	
	2 × 2 starter applicator	1.88	1.88
	Urea broadcast application	6.54	6.54
	Urea incorporation	13.61	13.61
	Coulter injection sidedressing	11.12	11.12
	Y-drop application	12.00	12.00
	Returns	——$ bu^{-1}——	
Price received	Corn grain	3.49	3.67

[a]Fertilizer and urease inhibitor costs were averaged from three local retailers: Nutrien Ag Solutions, Henderson, MI; Wilbur-Ellis, Three Rivers, MI; and Jorgensen Farm Elevator, Williamston, MI.

[b]Prices received were averaged from three local grain elevators: ADM Grain Co, Grand Ledge, MI; Michigan Agricultural Commodities, Middleton, MI; and Star of the West Milling Co, Richville, MI.

[c]Applications were estimated from the Michigan State University Extension Custom Machine and Work Rate Estimates (Stein, 2016).

Jorgensen Farm Elevator, Williamston, MI) were averaged to estimate product costs and were \$183 and \$305 ton^{-1} in 2017 and \$229 and \$360 ton^{-1} in 2018 for UAN and urea, respectively (Table 2). Urease inhibitor cost estimates from local retailers were \$130 gallon^{-1} for 2017 and 2018. Michigan State University Extension Custom Machine and Work Rate Estimates were used for application costs, specifically \$1.88, \$6.54, \$13.61, \$11.12, and \$12.00 acre^{-1} for 2 × 2 starter application, broadcast urea application, urea incorporation, Cinj sidedressing application, and YD sidedressing application, respectively, in 2017 and 2018 (Table 2) (Stein, 2016).

4 | STATISTICAL ANALYSIS

Data were subject to ANOVA via PROC GLIMMIX in SAS version 9.4 (SAS Institute, 2012) at $\alpha = .10$. Treatment, year, and location were considered as fixed effects, wheras replication was random. Residuals were assessed for normality via the UNIVARIATE procedure ($P \leq .05$). Homogeneity of variance was examined by Levene's test with the squared and absolute values of residuals ($P \leq .05$). Dunnett's test was used to compare each treatment with the nonfertilized control to confirm that a significant response to N fertilizer occurred ($P \leq .01$). Multiple df contrasts were constructed as the mean of treatments within each management strategy to compare data across N timing strategies, sidedressing methods, and the effects of a UI. Pearson's product–moment correlations were generated via the REG procedure of SAS to investigate the relationship between SPAD indices or NDVI measurements and grain yield.

5 | ENVIRONMENTAL CONDITIONS

Cumulative 2017 and 2018 growing season (April–September) precipitation was deficient across site-years, with shortages of 1.46 and 0.78 inches at Richville and 2.94 and 0.90 inches at Lansing from the respective 30-yr means (Table 3). Cumulative April and May precipitation at Richville differed by +23 and −21% from the 30-yr mean and by +23 and +15% at Lansing during 2017 and 2018, respectively. Deficit June to August precipitation (i.e., > 10% below the 30-yr mean) in Lansing during 2017 and 2018 probably limited the response to sidedressed N applications while increasing volatile N loss potential with surface applications (Maharjan, Rosen, Lamb, & Venterea, 2016; Stecker et al., 1993). Mean daily air temperatures for April 2017 were 4.5 °F above the 30-yr mean in both Richville and Lansing, whereas May air temperatures deviated by −0.7 to −1.4 °F. Air temperatures in April and May 2018 differed by −7.7 and +6.4 °F from the 30-yr mean in Richville and by −8.0 and +6.1 °F in Lansing, respectively. Mean air temperatures for June through September were within 10% of the 30-yr means across all site-years.

TABLE 3 Mean monthly precipitation and temperature[a] for the corn growing season at Richville and Lansing, MI, in 2017 and 2018

Site	Year	Apr.	May	June	July	Aug.	Sept.	Total
		inches						
Richville	2017	5.79	1.97	4.84	1.10	2.24	1.57	17.51
	2018	2.82	2.14	1.46	1.97	7.87	1.93	18.19
	30-yr avg.[b]	2.89	3.38	2.98	2.58	3.31	3.83	18.97
Lansing	2017	5.24	2.60	3.31	2.64	1.38	1.30	16.47
	2018	2.36	4.96	1.46	1.06	4.61	4.06	18.51
	30-yr avg.	3.03	3.36	3.45	2.84	3.23	3.50	19.41
		°F						
Richville	2017	50.6	56.6	68.7	70.2	66.7	64.2	–
	2018	38.4	63.7	67.6	71.8	71.3	64.1	–
	30-yr avg.	46.1	57.3	67.2	71.0	68.8	61.3	–
Lansing	2017	52.0	56.3	67.8	71.1	66.8	64.3	–
	2018	39.4	63.8	68.1	71.5	71.3	64.5	–
	30-yr avg.	47.4	57.7	67.6	71.5	69.8	61.9	–

[a]Monthly precipitation and air temperature data were collected from Michigan State University Enviroweather (https://enviroweather.msu.edu, accessed 12 June 2020).
[b]30-yr means were collected from NOAA (https://www.ncdc.noaa.gov/cdo-web/datatools/normals, accessed 12 June 2020).

6 | CORN GRAIN YIELD RESPONSE TO N STRATEGY

Grain yield was not influenced by N treatment, year, location, or any interaction ($P > .10$). Grain yield averaged between 166 to 183 bu acre^{-1} across site-years (Table 4). Environmental conditions affected nutrient loss potential and the lack of a corn yield response to N applications (Stecker et al., 1993). Soil moisture was greater in Richville (0.303–0.402 in^3 in^{-3}) than in Lansing (0.101–0.219 in^3 in^{-3}) across both years during the 21 d following N application (Table 5). However, dry soil conditions within the 21 d following N application combined with below-average cumulative growing season precipitation suggest that the grain yield response to N strategy was limited by rainfall frequency rather than soil moisture (Venterea & Coulter, 2015). Dry soil conditions may limit vertical N movement within the soil profile reducing root N uptake and inhibiting urea transformation into plant-available N (Gardinier et al., 2013; Maharjan et al., 2016; Venterea & Coulter, 2015).

Multiple df contrasts indicated that grain yield was not affected by N timing strategy ($P = .40$) (Table 4). Grain yield from the PRE, 50:50, 0:100, and 2 × 2 N timing strategies ranged from 170 to 180 bu acre^{-1} across site-years. Because of reduced June rainfall following sidedressing applications, dry soils may have resulted in decreased sidedressed N uptake and provided little yield benefit from the split N applications. Split N applications are a suggested practice to improve N recovery and nutrient use efficiency through greater synchronization of application timing with peak uptake (Cassman et al., 2002; Mueller et al., 2017; Rutan & Steinke, 2018). However, our results agree with Stecker et al. (1993) who suggested that single N applications at planting may be as effective as split applications when deficit rainfall limits sidedressed N movement into the root zone. Despite the nonsignificant data, delaying N applications until later in the season (V4–6) may allow producers the advantage of adjusting management practices and yield potentials according to environmental conditions. However, single-pass N applications at planting warrant consideration, as limited June and July soil moisture may limit N uptake and corn yield potential (Stecker et al., 1993).

Sidedressed N placement did not influence grain yield ($P = .31$), as CInj and YD surface applications resulted in mean grain yields of 180 and 174 bu acre^{-1}, respectively. Limited (≤0.31 inches) precipitation within the 7 d following sidedressing applications across all site-years may have limited N movement in the soil and reduced N uptake (Table 5). Moisture, plant-available nutrients, oxygen, and roots must simultaneously be in the same place for root nutrient uptake (Havlin, Tisdale, Beaton, & Nelson, 2014). Corn root densities are generally greater directly beneath the plant (Mengel & Barber, 1974) but precipitation soon after application would still be required with YD surface applications. Previous research comparing N placements at the same application time or growth stage found that similar or reduced grain yield and nitrogen use efficiency with surface N application relative to CInj (Fox & Piekielek, 1993; Fox et al., 1986; Woodley et al., 2018). The results from the current study suggest that YD surface N application at the base of the corn plant at

TABLE 4 Corn grain yield and net economic returns as affected by N timing strategies in combination with sidedressing placements and addition of a urease inhibitor, across locations and years at Richville and Lansing, MI, in 2017 and 2018

N strategy[a,b]	Grain yield[c]	Net economic return[d]
	bu $acre^{-1}$	\$ $acre^{-1}$
PRE	170	537[e] cd
PRE + UI	171	544 bcd
50:50: PPI–CInj	176	542 bcd
50:50: PPI–YD	168	524 cd
50:50: PPI–YD + UI	166	510 d
0:100: PPI–CInj	183	581 ab
0:100: PPI–YD	177	565 abc
0:100: PPI–YD + UI	180	566 abc
2 × 2 + CInj	183	593 a
2 × 2 + YD	177	560 abc
2 × 2 + YD + UI	176	552 abcd
P > *F*	.60	.08
Untreated[f]	95	312
Multiple df contrasts		
N timing[g]		
PRE	171	541 bc
50:50	170	525 c
0:100	180	571 a
2 × 2	179	569 ab
P > *F*	.40	<0.01
Sidedressing placement[h]		
CInj	180	572 a
YD	174	546 b
P > *F*	.31	.05
Urease inhibitor[i]		
–UI	172	547
+UI	173	543
P > *F*	.92	.78

[a]The maximum return to N rate used in Richville and Lansing was 170 and 145 lb N $acre^{-1}$, respectively.
[b]PRE, pre-emergence N application; UI, urease inhibitor; PPI, preplanting incorporation; 50:50, 50% of N incorporated before planting and 50% of N applied at V4 to V6 as sidedressing; 0:100, 100% of N applied at V4 to V6 sidedressing; 2 × 2, subsurface N application 2 in below and laterally from the seed; CInj, coulter injection; YD, Y-drop surface application.
[c]Grain yield at 15.5% moisture.
[d]Net economic return calculated as (yield × corn price) minus partial budget costs.
[e]Values within each column followed by the same lowercase letter are not significantly different at α = .10.
[f]The untreated control was not included in the statistical analysis.
[g]Contrasts consisted of two treatment means for the PRE N timing and three treatment means for the 0:100, 50:50, and 2 × 2 N timing strategies.
[h]The coulter injection multiple df contrast was the mean of all coulter injection treatments. Y-drop surface application was the mean of all treatments applying the Y-drop surface sidedressing method.
[i]The +UI multiple df contrast was the mean of all treatments containing a UI; –UI was the mean of all treatments not containing a UI.

V4 to V6 may be as effective as CInj during drier conditions. However, greater risk may exist with mid-season YD surface application because of increased volatilization potential, reduced N positional availability during limited precipitation, and daily wetting and drying cycles at the soil surface (Gardinier et al., 2013; Woodley et al., 2018). Greater benefits from YD surface placement may exist with late-season rescue N applications because of reduced leaf injury and greater canopy shading (Nelson et al., 2011).

Addition of a UI did not improve grain yield, suggesting that volatile N loss conditions may not have been present for a long enough time to observe a positive response to UI applications (Table 4). Precipitation events of 0.35 and 0.20 inches occurred 9 and 1 d in Richville after sidedressing application and 1.02 and 1.10 inches occurred 8 and 2 d after sidedressing application in Lansing during 2017 and 2018, respectively, which may have moved UAN into the root zone, reducing the likelihood of a grain yield response to the UI (Table 5) (Franzen, 2017). Nitrogen loss conditions must be present to observe a positive response from a UI (Quinn & Steinke, 2019).

7 | IMPACT OF NITROGEN STRATEGY ON NET RETURN AND EFFICIENCY

Net economic return was influenced by N strategy ($P = .08$) and is presented as an average across site-years, as there were no interactions among treatment, year, and location (Table 4). Within each N timing strategy, sidedressing or the addition of a UI did not influence net economic return, suggesting that application timing was a greater influence on profitability in the environments tested. Pearson's product–moment correlations revealed a positive relationship between grain yield and net return ($r = 0.98$, $P < .01$), indicating that strategies that numerically increased grain yield also increased net economic returns. However, the lack of significant grain yield differences emphasizes the importance of accounting for treatment costs when contemplating N strategy.

Multiple df contrasts indicated that the 0:100 and 2 × 2 N timing strategies increased net return by \$46 and \$44 $acre^{-1}$, respectively, compared with the 50:50 N timing strategy. Relative to split N applications (i.e. 50:50 N timing strategy), delaying N applications until V4 to V6 (i.e. 0:100 and 2 × 2 N timing strategies) probably reduced N loss potential. Because of the dry soil conditions in the current study, greater agronomic and economic benefits were obtained by delaying sidedressing applications until V4 to V6.

Despite a lack of significant grain yield differences, Cinj sidedressing placement increased net economic return by

TABLE 5 Mean soil moisture (in^3 in^{-3}) and cumulative precipitation[a] (in) 3 wk following corn N applications at Richville and Lansing, MI, in 2017 and 2018

		N applications initiated at planting[b]			Sidedressed N applications[c]		
		0–7 d	8–14 d	15–21 d	0–7 d	8–14 d	15–21 d
		Mean soil moisture					
Location	Year	in^3 in^{-3}					
Richville	2017	0.316	0.303	0.304	0.315	0.395	0.402
	2018	0.348	0.356	0.358	0.376	0.374	0.372
Lansing	2017	0.143	0.153	0.172	0.101	0.131	0.159
	2018	0.187	0.219	0.206	0.207	0.189	0.186
		Precipitation					
		in					
Richville	2017	1.30	0.04	0.24	0.00	2.17	2.05
	2018	0.63	0.79	0.43	0.28	0.12	0.20
Lansing	2017	0.04	1.57	0.00	0.20	2.76	0.28
	2018	2.68	0.91	0.00	0.31	0.35	0.35

[a]Mean soil moisture at 0 to 12 inch), and cumulative precipitation data were collected from Michigan State University Enviroweather (https://enviroweather.msu.edu, accessed 12 June 2020).

[b]Applications include pre-emergence application (PRE), PRE with a urease inhibitor, and pre-plant incorporation. Applications were made on 28 April 2017 and 1 May 2018 in Richville and on 12 May 2017 and 8 May 2018 in Lansing.

[c]Applications include coulter injection, Y-drop surface application, and Y-drop surface application with a urease inhibitor. Applications were made on 6 May 2017 and 31 May 2018 in Richville and on 9 June 2017 and 7 June 2018 in Lansing.

\$26 acre^{-1} compared with YD surface placement. Soil moisture is often greater beneath the soil surface than on top of the soil surface. Subsequently, subsurface N placement (i.e., CInj) may better support the economic investment in N fertilizer through increased potential for root N uptake and reduced potential for volatile N loss (Havlin et al., 2014; Woodley et al., 2018). The addition of a UI to the PRE timing strategy or with YD surface application did not affect the net return and required greater input costs. Producers often perceive yield loss as a greater risk than profitability but instead may need to justify agronomic inputs (e.g., integrated pest management) and balance both grain production and economic return by considering input cost and nutrient placement in addition to potential yield benefits (Rutan & Steinke, 2018).

Treatment, year, location, and N timing × placement interactions did not influence AE ($P > .10$) (Table 6). Dry soil conditions were previously reported to reduce AE by causing limited N uptake and mobility within the soil profile (Steinke, Rutan, & Thurgood, 2015). When averaged across site-years and placement strategies, the 0:100 and 2 × 2 N timing strategies increased AE indicating greater grain production per unit of N fertilizer applied. These results agree with Rubin et al. (2016), who reported a 6% increase in AE with split applications of urea compared with a single at-planting application. Across site-years, AE decreased from 30.4 lb grain lb^{-1} N with CInj sidedressing placement to 28.2 lb grain lb^{-1} N with YD surface application. The reduced AE with YD surface application emphasizes the difficulty of N recovery when limited precipitation (≤0.31 inches) follows N application, preventing N mobility into the rooting zone. Addition of a UI did not significantly influence AE. Despite a lack of grain yield differences, improved AE with the 0:100 and 2 × 2 N strategies and CInj sidedressing placement reduced the potential for environmental N loss (Rubin et al., 2016).

8 | NITROGEN STRATEGY EFFECTS ON PLANT GROWTH AND GREENNESS

Nitrogen application timing and year influenced mean V6 NDVI measurements ($P = .02$, Table 7). Because of the NDVI measurements occurred within 6 d of sidedressed N application and limited precipitation following application, data were averaged across sidedressing placement methods and UI addition. No differences in V6 NDVI were observed in 2017, suggesting limited plant responses to N timings. Bender, Haegele, Ruffo, & Below (2013) reported that season-long N accumulation prior to V6 was less than 15%. Corn yield potential determination occurs up until the V8 growth stage and thus earlier NDVI measurements can give inaccurate yield estimates (Teal et al., 2006). In 2018, the 0:100 N timing strategy reduced V6 NDVI compared with the PRE, 50:50, and 2 × 2 N timing strategies. Tucker (1979) reported that red NDVI was an indicator of green biomass and plant growth. Delaying 100% of N until sidedressing (i.e., the 0:100 N timing strategy)

TABLE 6 Agronomic efficiency of applied corn N fertilizer[a] compared across main effects of N timing strategy, V4 to V6 sidedressing placement,, and addition of a urease inhibitor (UI) with multiple df contrasts across locations and years at Richville and Lansing, MI, in 2017 and 2018

N timing[b,c]	Agronomic efficiency[d]
	——lb grain lb^{-1} N——
PRE	26.9 b[e]
50:50	26.6 b
0:100	30.2 a
2 × 2	29.9 a
P > *F*	.03
Sidedressing placement[f]	
CInj	30.4 a
YD	28.2 b
P > *F*	.09
UI[g]	
–UI	27.7
+UI	28.0
P > *F*	.86

[a]The maximum return to N rate used in Richville and Lansing was 170 and 145 lb N acre^{-1}, respectively.
[b]Contrasts consisted of two treatment means for the pre-emergence (PRE) N timing and three treatment means for the 0:100, 50:50, and 2 × 2 N timing strategies.
[c]50:50, 50% of N incorporated before planting and 50% of N applied at V4 to V6 as sidedressing; 0:100, 100% of N applied at V4 to V6 sidedressing; 2 × 2, subsurface N application 2 in below and laterally from the seed; CInj, coulter injection; YD, Y-drop surface application.
[d]Agronomic efficiency was calculated by subtracting the yield of the unfertilized control from the mean yield of treatments with N and dividing this by the N rate.
[e]Values within each column followed by the same lowercase letter are not significantly different at α = .10.
[f]The coulter injection multiple df contrast was the mean of all coulter injection treatments; Y-drop surface application was the mean of all treatments applying the Y-drop surface sidedressing method.
[g]The UI multiple df contrast was the mean of all treatments containing a UI; –UI was the mean of all treatments not containing a UI.

reduced early season plant growth in 2018during more consistent rainfall periods emphasizing the importance of satisfying N requirements prior to sidedressing application (Rutan & Steinke, 2018). Pearson's product–moment correlations suggested no relationship ($P > .10$) between grain yield and V6 NDVI in either year, indicating that increased green dry matter at V6 did not result in greater yield.

Mean V10 NDVI data were not affected by year or location ($P = 0.43$) and are presented as a mean across site-years (Table 7). Multiple df contrasts indicated that NDVI was reduced by 3.0 and 4.2% with the 0:100 N timing strategy compared with PRE and 2 × 2, respectively. However, poor relationships between V10 NDVI and grain yield ($r = 0.20$, $P < 0.01$) suggests that a late-vegetative (V10) NDVI response to N timing may not influence grain production. Accelerated rates of dry matter production and N accumulation occur between V10 and V14 (Bender et al., 2013) and may diminish the plant response to early-season N applications if sufficient N is available. The results of active canopy sensing at V10 suggest that the 2 × 2 N timing strategy may allow growers to use reduced N rates at planting, thereby reducing the risks of N loss while still satisfying early corn N requirements for optimal growth.

TABLE 7 Multiple df contrasts comparing N timing strategies on mean canopy normalized difference vegetation index (NDVI) measurements at V6 across locations (Richville and Lansing, MI) in 2017 and 2018 and at V10 across years and locations

N timing[a,b]	V6 NDVI[c] 2017	V6 NDVI[c] 2018	V10 NDVI 2017–2018
	——————NDVI——————		
PRE	0.311	0.441[d] a	0.777 a
50:50	0.306	0.435 a	0.773 ab
0:100	0.312	0.386 b	0.755 b
2 × 2	0.325	0.431 a	0.787 a
P > *F*	.13	<.01	.04
Untreated[e]	0.281	0.398	0.715
Pearson's product–moment correlation[f]			
r	0.10	0.10	0.20
P > *F*	.34	.31	<.01

[a]Contrasts consisted of two treatment means for the pre-emergence (PRE) N timing and three treatment means for the 0:100, 50:50, and 2 × 2 N timing strategies.
[b]50:50, 50% of N incorporated before planting and 50% of N applied at V4 to V6 as sidedressing; 0:100, 100% of N applied at V4 to V6 sidedressing; 2 × 2, subsurface N application 2 in below and laterally from the seed.
[c]Measurements were taken within 2 to 6 d of sidedressing application at each site-year.
[d]Values within each column followed by the same lowercase letter are not significantly different at α = .10.
[e]The untreated control was not included in the statistical analysis.
[f]Pearson's product–moment correlation between grain yield and V6 or V10 NDVI measurements.

Chlorophyll meter measurements were used to indicate N status. A treatment × year interaction occurred at R1 ($P = .03$) and CM values were combined across locations within each year (Table 8). Within the 50:50 timing strategy and compared with CInj, YD surface application reduced CM values at the R1 stage in 2017 but increased these values in 2018. Minimal precipitation (≤0.20 inches) 7 d following sidedressed N application in 2017 may have limited N uptake and R1 chlorophyll production with YD surface application (Table 5). During 2018, precipitation events totaling 0.28 and 0.30 inches occurring within 4 d of sidedressing application in Richville (one event) and Lansing (two events), respectively, suggested that wetting fronts may have moved N into the root zone for N uptake and subsequent chlorophyll production under the YD surface application. Treatment differences in both years were

TABLE 8 Corn SPAD chlorophyll[a] as affected by N timing strategies in combination with sidedressing placements and addition of a urease inhibitor (UI) at R1 across locations (Richville and Lansing, MI) in 2017 and 2018 and at R4 across years and locations

	R1 chlorophyll		R4 chlorophyll
N strategy[b]	2017	2018	2017–2018
PRE	56.9[c] a	49.6 b	46.8 cd
PRE + UI	55.0 abc	50.7 ab	49.1 ab
50:50: PPI–CInj	55.5 ab	48.3 c	47.2 cd
50:50: PPI–YD	53.3 c	50.4 b	46.7 d
50:50: PPI–YD + UI	54.0 bc	50.5 b	48.6 bcd
0:100: PPI–CInj	56.9 a	50.9 ab	50.2 ab
0:100: PPI–YD	56.3 a	51.2 ab	48.6 bcd
0:100: PPI–YD + UI	55.3 abc	53.1 a	51.0 a
2 × 2 + CInj	56.2 a	51.2 ab	49.2 ab
2 × 2 + YD	55.6 ab	53.0 a	50.8 a
2 × 2 + YD + UI	56.5 a	51.8 ab	50.2 ab
P > *F*	.07	<.01	<.01
Untreated[d]	39.5	40.9	27.4
Multiple df contrasts			
Nitrogen timing[e]			
PRE	56.0 a	50.1 bc	48.0 b
50:50	54.3 b	49.6 c	47.5 b
0:100	56.1 a	51.7 ab	49.9 a
2 × 2	56.1 a	52.0 a	50.1 a
P > *F*	.03	<.01	<.01
Sidedress placement[f]			
CInj	56.2 a	50.1 b	48.9
YD	55.1 b	51.6 a	49.3
P > *F*	.09	.04	.42
Urease inhibitor[g]			
–UI	55.5	51.0	48.3 b
+UI	55.2	51.4	49.7 a
P > *F*	.57	.60	<.01
Pearson's product–moment correlation[h]			
r	0.75	0.67	0.94
P > *F*	<.01	<.01	<.01

[a] Average of 10 plant measurements taken halfway between the leaf collar and leaf tip.
[b] PRE, pre-emergence N application; UI, urease inhibitor; PPI, preplanting incorporation; 50:50, 50% of N incorporated before planting and 50% of N applied at V4 to V6 as sidedressing; 0:100, 100% of N applied at V4 to V6 sidedressing; 2 × 2, subsurface N application 2 in below and laterally from the seed; CInj, coulter injection; YD, Y-drop surface application.
[c] Values within each column followed by the same lowercase letter are not significantly different at $\alpha = .10$.
[d] The untreated control was not included in the statistical analysis.
[e] Contrasts consisted of two treatment means for the PRE N timing and three treatment means for the 0:100, 50:50, and 2 × 2 N timing strategies.
[f] The coulter injection multiple df contrast was the mean of all coulter injection treatments; Y-drop surface application was the mean of all treatments applying the Y-drop surface sidedressing method.
[g] The UI multiple df contrast was the mean of all treatments containing a UI; –UI was the mean of all treatments not containing a UI.
[h] Pearson's product–moment correlation between grain yield and R1 or R4 chlorophyll measurements.

mostly caused by the time of application, as sidedressing placement and addition of a UI did not affect R1 CM values in the PRE, 0:100, and 2 × 2 N timing strategies. Multiple df contrasts indicated that N timing strategies influenced R1 CM values during 2017 ($P = .03$) and 2018 ($P < .01$). Similar trends in the data were observed both years for the 50:50 N timing strategy, which reduced R1 CM values by 3.3 to 4.8% relative to the PRE, 0:100, and 2 × 2 N timing strategies, indicating some degree of N loss prior to side-dressing application. The PRE N timing strategy increased early-season N concentrations in the rooting zone, which may have offset some degree of N loss, resulting in greater R1 CM than under the 50:50 N timing strategy. However, increasing N availability (the 0:100 and 2 × 2 N timing strategies) during peak uptake periods may sustain chlorophyll production. Multiple df contrasts indicated that CInj sidedressing placement increased R1 CM values during 2017 but decreased chlorophyll production relative to YD surface placement during 2018. The data suggest CInj sidedressing placement may increase plant R1 N status during minimal precipitation following sidedressing application, but YD surface application was more effective when moisture was adequate for nutrient uptake. Addition of a UI did not affect R1 CM values in either year.

Chlorophyll meter data at the R4 stage were influenced by N strategy (P = .04) but not year or location and are presented across site-years (Table 8). The effect of N timing strategy on R4 CM values closely follow the R1 measurements, where delaying N applications until V4 to V6 (i.e., 0:100 and 2 × 2) increased chlorophyll concentrations. No differences were observed in R4 CM values with sidedressing placement strategies, but the addition of a UI increased R4 CM values despite no differences in grain yield occurred, suggesting that delayed urea hydrolysis may have increased N availability for midseason chlorophyll production (Warncke et al., 2009). A positive relationship between grain yield and R4 CM values ($r = 0.94$, $P < .01$) indicated greater plant N status and chlorophyll production translated into increased grain yield.

9 | IMPLICATIONS FOR CORN PRODUCTION

The results demonstrate the difficulty of improving N management strategies and grain yield during the dry soil conditions encountered in the environments tested. Minimal precipitation following application and during peak N uptake produced nominal grain yield differences produced by N application timing, sidedressing placement, or addition of a UI. Precipitation frequency affects corn grain yield responses to N timing and placement methods, and forecasts of weather patterns should be considered when deliberating among N management strategies. The improved AE of N applied by the 2 × 2 and 0:100 N timing strategies compared with the 50:50 and PRE strategies suggested greater N utilization with V4 to V6 N applications. Greater moisture beneath the soil surface than on the soil surface emphasizes the potential for positional unavailability of surface-applied N applications for plant uptake during dry conditions which may explain the greater AE and profitability with CInj compared with YD in this study. The benefits of YD surface application may be better realized during late-season rescue N applications that restrict CInj application, when precipitation immediately follows N application, or during adequate surface moisture conditions. Mid-season N applications offer the flexibility to adjust N strategy (i.e., N rate, sidedressing placement, addition of a UI) on the basis of already encountered or predicted environmental conditions, but preplanting N strategies are still effective, especially when dry midseason conditions restrict N uptake. Concerns for both climate variability and Great Lakes water quality will continue to place more emphasis on N management strategies that reduce nutrient loss and improve profitability. Corn growers can adapt to climate variability by adjusting N application timings and sidedressing placement, but modifications may require additional infrastructure and flexibility in decision-making, which may not be practical across individual operations. Additional research involving similar treatments and comparisons across multiple production management systems and soil classifications under a variety of environmental conditions will further enhance the corn N management toolbox.

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CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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