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Split-nitrogen application with cover cropping reduces subsurface nitrate losses while maintaining corn yields

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Abstract

Artificial subsurface drainage is essential to sustain crop production in many areas but may also impair water quality by exacerbating nitrate (NO_3)–nitrogen (N) delivery downstream. Cover crops and split-N application have been promoted as key conservation practices for reducing NO_3–N losses, but few studies have simultaneously assessed their effect on water quality and crop productivity. A field study was conducted to evaluate the effects of N application timing and cover crops on subsurface drainage NO_3–N losses and grain yield in continuous corn (*Zea mays* L.). Treatments were preplant-N: 224 kg N ha^{-1} split-applied with 60% fall + 40% preplant in 2018, or as single preplant applications in 2019 and 2020; split-N: 40% preplant + 60% side-dress (V6–V7); split-N + cover crop (CC): Split-N + cereal rye (*Secale cereale* L.); and a zero N plot as the control. Across the 3-yr study period, split-N + CC significantly reduced flow-weighted NO_3–N concentration and NO_3–N loss by 35 and 37%, respectively, compared with preplant-N. However, flow-weighted NO_3–N concentration (4.3 mg L^{-1}) and NO_3–N loss (22.4 kg ha^{-1}) with split-N were not significantly different from either preplant-N (4.8 mg L^{-1} and 26.4 kg ha^{-1}, respectively) or split-N + CC (3.1 mg L^{-1} and 16.7 kg ha^{-1}, respectively). Corn yield was significantly lower in the control treatment but did not differ among N fertilized treatments in any year. These results indicate that combining split-N application with cover crops holds promise for meeting the statewide interim milestone NO_3–N reduction target of 15% by 2025 without negatively impacting crop productivity.

1 | INTRODUCTION

Agricultural nitrogen (N) contributions to water quality degradation through nitrate (NO_3)–N leaching losses have become a relevant concern in the U.S. Midwest. Elevated riverine NO_3–N concentrations in the Mississippi River basin have been attributed to the combination of croplands with high N inputs and subsurface drainage systems across much of this region (David et al., 2010; Dinnes et al., 2002), contributing significantly to the seasonal hypoxic zone in the Northern Gulf of Mexico each year (USEPA, 2007). In response, Illinois and other states have developed individual nutrient loss reduction strategies outlining the most effective in-field and edge-of-field practices for improving water quality. Of the in-field management strategies outlined in the Illinois Nutrient Loss Reduction Strategy (IEPA et al., 2015), improved N management (e.g., N rate and timing) and the

Abbreviations: RM, relative maturity; UAN, urea-ammonium-nitrate; WY, water year.

use of winter cover crops have received great attention from researchers, extension professionals, and the retail agriculture industry.

Fall N application with anhydrous ammonia is a common practice in Illinois because of the lower cost compared with other N fertilizer sources and the advantage of distributing the workload before planting (Gentry et al., 2014). However, because N is applied 5–6 mo before corn (*Zea mays* L.) planting, there is a higher potential for N losses following fall N application, especially in years with mild winters and wet springs. Previous studies have shown greater reductions in subsurface drainage NO_3–N loss (Randall & Vetsch, 2005a; Randall et al., 2003a) and corn yield improvements with a single spring versus fall N applications (Randall & Vetsch, 2005b; Randall et al., 2003b). Alternatively, N applications can also be split between fall and spring, which corresponds to an estimated 10% reduction in NO_3–N losses compared with a single fall application in the Illinois Nutrient Loss Reduction Strategy (2015).

Another commonly recommended option to reduce the risk of NO_3–N leaching losses is to synchronize soil N supply to crop N demand (Cassman et al., 2002; Robertson & Vitousek, 2009). For corn in Illinois, this could be achieved by splitting N applications between planting time and the beginning of rapid crop growth and N uptake (stage V6–V8). Although this approach is considered part of the 4R's of nutrient stewardship (right source, right rate, right time, and right place; The Fertilizer Institute, 2020), few studies have simultaneously assessed the effects of fall or spring versus split-N applications between preplant and side-dress on water quality and grain yields (Eagle et al., 2017). In a corn–soybean [*Glycine max* (L.) Merr.] rotation in Iowa, Jaynes (2015) found no significant differences in NO_3–N losses when anhydrous ammonia was applied either in the fall, preplant, or at side-dress but found higher corn yields with side-dress compared with fall applications. Randall et al. (2003a; b) reported that split-N (preplant + side-dress) significantly increased grain yields compared with fall or preplant-N, but NO_3–N losses were not affected by N application timing.

Cover crops can reduce NO_3–N loss in subsurface drainage fields by taking up water and inorganic N during the fallow period (Dinnes et al., 2002; Strock et al., 2004). Cereal rye (*Secale cereale* L.) has been widely used in the upper Midwest because of its winter-hardiness and its ability to scavenge postharvest soil N compared with other species (Kaspar & Bakker, 2015). While previous studies have shown reductions in NO_3–N concentrations in subsurface drainage provided by cereal rye (Kaspar et al., 2007, 2012; Ruffatti et al., 2019; Waring et al., 2020), many producers remain apprehensive about cover crop adoption. One of the obstacles of planting cereal rye ahead of corn is the potential reduction of early-season soil N availability due to net N immobilization, resulting in 0.1–12% yield reductions (Crandall et al., 2005; Pantoja et al., 2015; Patel et al., 2019). Yet, a recent meta-analysis found little evidence of consistent yield decline of corn following a nonlegume winter cover crop (Marcillo & Miguez, 2017). Moreover, few studies have quantified how split-N application (preplant + side-dress) combined with cover crop influences NO_3–N losses and grain yield compared with a system based on fall or spring N applications. The ability to pair practices such as cover cropping and split-N application could be a major component for meeting water quality goals in the Mississippi River basin (Christianson et al., 2018), but published evidence on the effectiveness of this approach is lacking.

When evaluating in-field conservation practices to meet ambitious water quality goals in Illinois, it is essential to avoid situations where reductions in NO_3–N losses are accompanied by reductions in grain yields. Therefore, a better understanding of potential risks and tradeoffs between water quality and crop productivity is necessary to increase the adoption of these practices by producers in Illinois (Marks & Boerngen, 2019). The objectives of this study were (a) to determine whether split-N application (preplant + side-dress) reduces NO_3–N losses compared with preplant-N application, (b) to assess if combining a cereal rye cover crop with split-N applications has greater impacts on NO_3–N losses compared with preplant or split-N application alone, and (c) to evaluate the effects of N application timing and cover crop on corn grain yields.

Core Ideas

- Water quality and yield impacts of N timing and cover crop were assessed for 3 yr.
- Cover crop biomass and N uptake were low when growing conditions were poor.
- Split-N application did not reduce N losses compared with preplant-N.
- Split-N + cover crop reduced N losses compared with preplant-N but not split-N alone.
- Grain yield was not affected by N application timing or cover crop.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

This study was conducted from fall 2017 through fall 2020 at a replicated subsurface drainage experiment established in 2016 at the University of Illinois Dudley Smith Farm in Christian

County, IL (39°26′56″ N, 89°6′43″ W). A detailed description of the site and drainage system was provided by Preza Fontes et al. (2019). Briefly, the site has 30-yr average annual precipitation of 1,043 mm (1981–2010, excluding melted snow) (http://mrcc.illinois.edu, ID: USC00116579). The predominant soil is a Virden silty clay loam (fine, smectitic, mesic Vertic Argiaquolls), classified as poorly drained, with 0–2% slopes (Web Soil Survey, 2021). Average soil properties with depth are shown in Supplemental Table S1. Weather data was recorded using an on-site weather station (HOBO® RX3000, Onset Computer Co.).

The site consists of 16 individually subsurface drainage plots of ∼0.85 ha each. Each plot contains three tile laterals of 10.2 cm diameter spaced 18.2 m apart, and it is hydrologically isolated using border tiles of same diameter and spacing. The corrugated plastic tile drains were installed at a depth of 1.0–1.1 m with a 0.1% slope using a drainage coefficient of 9.5 mm d^{-1}.

The site was in a corn–soybean rotation with conventional tillage before starting the experiment and was converted to continuous corn after installing the subsurface drainage system. Corn was grown with uniform management across plots in 2017 (baseline year without treatments; see Preza Fontes et al. [2019] for more details). The current study began in fall 2017 when treatments were first imposed for the crop-year 2018. Soil tests from samples obtained at the beginning of the study showed adequate levels of P, K, and pH (Supplemental Table S2). The experiment was arranged in a randomized complete block design with four replications. The fertilized treatments received 224 kg N ha^{-1}, which is within the maximum return to N profitable N rate range for corn following corn in central Illinois (http://cnrc.agron.iastate.edu). Treatments included three combinations of N fertilizer timing and cereal rye cover crop, plus a control treatment with no N applied. The preplant-N treatment for the 2018 season consisted of a fall application of 134 kg N ha^{-1} as anhydrous ammonia + nitrapyrin at 0.56 kg a.i. ha^{-1} (N-Serve®, Corteva Agriscience) followed by a preplant application of 90 kg N ha^{-1} as urea-ammonium-nitrate (UAN, 32–0–0). The nitrapyrin was mixed in the anhydrous ammonia tank and the N fertilizer was injected at 20-cm depth below soil surface using a 6000 Pull-Type Toolbar (Hiniker). The UAN was injected between rows at 3.5-cm depth using a flat-coulter applicator (BLU-JET AT6020, Thurston Manufacturing). Wet soil conditions in the fall of 2018 and 2019 precluded fall N application, so in 2019 and 2020, preplant-N consisted of a single preplant application of 224 kg N ha^{-1} using injected UAN as previously described. The split-N treatment consisted of a 40:60 preplant/side-dress (at V6–V8 growth stage) (Abendroth et al., 2011) at 90 and 134 kg N ha^{-1}, respectively, both done using injected UAN. The third treatment, split-N + (cover crop) CC, consisted of the split-N treatment as previously described plus a cereal rye cover crop planted the previous fall and terminated 2–4 wk before planting. Preplant-N applications were made within 1 wk of corn planting (Supplemental Table S3).

2.2 | Subsurface drainage water monitoring

Each plot drained to an inline water level control structure (AgriDrain) containing a 45° V-notch weir stop log placed at the bottom. Drainage flow was continuously monitored in all plots using an automated sampler paired with a logging pressure transducer (6712 Full-size Portable Sampler with a 720-probe flow module, Teledyne, ISCO; or with a U20L-04 Water Level Logger, Onset Computer Co.). Water levels logged every 15 min were compiled into daily averages, and a daily average flow rate was calculated using either a calibrated V-notch weir equation or a compound weir equation at greater flow depths (AgriDrain, personal communication, 15 Apr. 2017; Chun & Cooke, 2008). Water levels in each control structure were also manually measured during site visits to verify data accuracy based on visual observation. The maximum drainage flow was set to 1.57 L s^{-1} for each plot in data postprocessing based on Manning's equation and assuming full pipe flow. In flooding events following high rainfall occurrences (e.g., 177 mm on 11–12 June 2018), the water level inside the control structure rose above levels that generated the maximum drainage flow rate (sometimes >1 m water depth). In these situations, the flow rate was assumed 0 L s^{-1} (due to an assumed flooded outlet) until water levels began to decline below the maximum flow rate.

From fall 2017 through summer 2019, daily water samples of 800 ml were collected from each plot (composite from four 200-ml samples taken every 6 h). Beginning in fall 2019, water samples were composited over a 2-d period (from eight 100 ml samples taken every 6 h), which still allowed >90% probability of estimating annual NO_3–N loss within ±15% of the "true" annual loss (Wang et al., 2003). Drainage water samples were collected from automated samplers weekly or biweekly, filtered within 24 h (0.45 μm, S-Pak Membrane Filters, Millipore Sigma), and stored frozen until analysis. Samples were typically analyzed within 20 d in 2018 and 2019, but storage times in 2020 were longer (5–6 mo) due to global pandemic restrictions. Water samples were analyzed for NO_3–N concentration using a colorimetric method with a minimum detection limit of 0.01 mg L^{-1} (method 10-107-106-1-J, Lachat QuickChem 8500 series, Hach Co.). Annual NO_3–N loss was estimated for each plot by multiplying NO_3–N concentrations with flow volumes between the previous sample and the current event and summing over all samples for each water year (WY; 1 October to 30 September). Flow-weighted NO_3–N concentrations were estimated by dividing annual NO_3–N loss by annual discharge volumes. Yield-scaled NO_3–N leaching losses (kg NO_3–N Mg^{-1} of grain produced) were estimated by dividing NO_3–N losses by grain yield for each plot.

2.3 | Cover crop and corn management

A summary of management practices is shown in Supplemental Table S3, including dates of CCs planting and termination, corn planting and harvest, postharvest soil sampling, tillage, and N fertilizer applications. The cereal rye (variety not stated) was planted after corn harvest in 2017 and 2018 at 67 kg ha^{-1} on 19-cm rows using a 4555 no-tillage drill (Deere & Co.). To provide increased time for fall establishment and growth, the cereal rye was seeded at 73 kg ha^{-1} into standing corn (R5 growth stage) in 2019 using a high-clearance Hagie Sprayer STS10 (Deere & Co.). In all years, the rye was terminated in the spring by spraying glyphosate [N-(phosphonomethyl)glycine] at 1.29 kg a.i. ha^{-1}. Before termination, aboveground biomass was randomly collected from a 1-m^2 area at five locations in each plot. Samples were dried at 60 ˚C in a forced-air oven, ground to pass a 2-mm screen using a Wiley mill (Arthur H. Thomas Co.), and analyzed for total N and C by A&L Great Lakes Laboratories.

Corn was planted with 76-cm row spacing at 86,500 seeds ha^{-1} in all years. Wyffels Hybrid W7976RIB (113 relative maturity [RM]), W5518RIB (109 RM), and W7888RIB (114 RM) were used in 2018, 2019, and 2020, respectively. Before corn planting in 2018 and 2019, all plots were sprayed with 1.6 kg a.i. ha^{-1} of glyphosate [N-(phosphonomethyl)glycine] plus 0.31 kg a.i. ha^{-1} of 2,4-D (2,4-dichloro-phenoxyacetic acid). A pre- and postemergence herbicide application were done in 2020. The pre-emergence consisted of applying 0.93 kg a.i. ha^{-1} of glyphosate plus 0.8 kg a.i. ha^{-1} of atrazine [2-chloro-4-(ethylamino)−6-(isopropylamino)-s-triazine]. The same rate of glyphosate and atrazine was applied on 17 June 2020 for the postemergence program, plus 0.4 kg a.i. of topramezone [3-(4,5-dihydro-3-isoxazolyl)−2-methyl-4-(methylsulfonyl)phenyl](5-hydroxy-1-methyl-1H-pyrazol-4-yl) methanone.

Fall strip-tillage was conducted in all 16 plots using a 6000 Pull-Type Toolbar (Hiniker) at the same time as fall N fertilizer application in 2017. Wet soil conditions in the fall of 2018 and 2019 prevented strip-tillage and fall N application, so a strip-freshener (Yetter Manufacturing) was used in the spring of 2019 and 2020 to prepare the seedbed before corn planting in all plots. Phosphorus (P; triple super phosphate, 0–45–0) and potassium (K; muriate of potash, 0–0–60) fertilizer were broadcast applied on 15 Nov. 2017 at 357 kg P ha^{-1} and 112 kg K ha^{-1}, respectively. Because soil test P and K were at adequate levels according to the Illinois Agronomy Handbook (Fernández & Hoeft, 2009), fertilizers were applied in a single-application at rates equivalent to expected crop removal for the 3-yr study period.

Corn was harvested using a John Deere Combine equipped with a GREENSTAR Yield Monitor System and Yield Mapping System (Deere & Co.). ArcMap Software v10.7 (ESRI) was used for yield data cleaning (removal of values more than 3 SDs from the mean, according to Sudduth et al., 2012) and calculating average yield (adjusted to 15 g kg^{-1} moisture) for each plot. The number of yield data points used within each plot was usually between 300 and 400.

2.4 | Postharvest soil sampling and analysis

Six soil cores (3.2-cm diameter) were taken from each plot after corn harvest. The soil cores were taken mid-way between rows to a 90-cm depth using a tractor-mounted hydraulic probe and were divided into four depth increments (0–15, 15–30, 30–60, and 60–90 cm). Cores were composited for a total of four samples (depth increments) per plot. Soil inorganic N was extracted within 48 h using 2 M KCl (12 g of field moist soil in 100 ml extraction, shaken for 1 h), filtered (8 µm, Whatman filter paper No. 2), and analyzed for NO_3–N using a Smartchem 170 discrete wet chemistry auto-analyzer (Unity Scientific). Soil NO_3–N (kg ha^{-1}) for each depth increment was calculated using its respective soil bulk density.

2.5 | Statistical analysis

Analysis of variance (ANOVA) was conducted using PROC GLIMMIX of SAS v9.4 (SAS Institute). For each year, response variables were analyzed using a randomized complete block design, with treatment as fixed effects and block as random effects. A second ANOVA was performed to evaluate the treatment effects across the 3-yr study period, with year and block nested within year as random factors. Residuals were assessed for normality using the Shapiro–Wilk test with PROC UNIVARIATE. When needed, data were square root transformed to fulfill the assumptions of normal distribution and equal variances. After ANOVA, the data were back-transformed to the original scale to aid interpretation. The unfertilized control treatment was not included in the ANOVA for the yield-scaled NO_3–N loss. Because grain yield was low when no N was applied, yield-scaled NO_3–N losses from that control were >fourfold higher compared with the fertilized treatments, and the ANOVA assumptions were not met even when data were transformed. Treatment effects were considered significant at $p \leq .1$. Least square means were compared using Fisher's LSD method with the LINES option.

TABLE 1 Deviation from the 30-yr average (1981–2010) of average monthly total precipitation and air temperature for the water years[a] 2018–2020 at the University of Illinois Dudley Smith Farm, Christian County, IL

	Precipitation				Air temperature			
	30-yr	2018	2019	2020	30-yr	2018	2019	2020
	mm				°C			
Oct.	90	+47	−32	+31	13.3	+1.3	−0.2	−0.7
Nov.	105	−69	−39	−56	7.0	−0.7	−4.6	−4.3
Dec.	76	−70	+13	−11	−0.3	−0.3	+1.8	+2.2
Jan.	60	−39	+1	+74	−1.9	−1.3	−0.9	+2.4
Feb.	54	+59	−8	−11	0.6	+0.9	−0.7	−0.2
Mar.	77	+25	+71	+10	6.1	−1.9	−2.5	+1.5
Apr.	100	−38	−8	+50	12.5	−4.5	−0.2	−2.0
May	114	−29	+65	+47	17.7	+4.7	+0.5	−1.3
June	116	+152	+112	+13	22.7	+1.4	−0.3	+1.1
July	99	+37	−24	+58	24.7	−1.2	+0.7	+1.1
Aug.	74	+40	+47	−57	23.5	−0.1	−0.6	−0.4
Sept.	85	−40	−7	−70	19.7	−1.8	+2.7	−0.7
Annual	1,050	+74	+192	+78	12.1	−0.1	−0.4	−0.1

[a]Water year is defined from 1 Oct. of the previous year to 30 Sept. of that year.

3 | RESULTS AND DISCUSSION

3.1 | Weather impacts on subsurface drainage flow

Annual precipitation was greater in all years compared with the 30-yr average in the region (Table 1). The most precipitation occurred in WY 2019 (1,242 mm, 18% above the long-term average), followed by 2020 (1,129 mm) and 2018 (1,124 mm). Monthly precipitation varied over the 3-yr study period, with the most precipitation occurring in June 2018 (267 mm) and 2019 (227 mm), and the least in December 2017 (5 mm). Monthly air temperature also varied within and among years compared with the long-term average, with the greatest deviation in April and May 2018, and November 2019 and 2020 (± 4˚C). Average temperatures were below the 30-yr average in November, April, and August in all years. In contrast, December was warmer than the long-term average in both 2019 and 2020, as well as January and March in 2020.

Annual subsurface drainage discharge was not significantly affected by treatments in any year or when the 3 yr were analyzed together (Table 2). Across treatments, subsurface drainage represented 32, 58, and 63% of the annual precipitation in WY 2018, 2019, and 2020, respectively. Most of the annual drainage generally occurs between March and June in colder regions in the upper U.S. Midwest (e.g., Jin & Sands, 2003; Randall & Vetsch, 2005a; Randall et al., 2003a). In regions where the soil does not freeze all winter, subsurface drainage is concentrated during the fallow season of November through April (Kladivko & Bowling, 2021). In WY 2018, winter drainage was low due to low precipitation in late 2017 and early 2018, with 59% of the annual drainage occurring between March and June when averaged across treatments. In contrast, 75 and 70% of the total annual drainage occurred between December and May in 2019 and 2020, respectively, corresponding to 44% of annual precipitation. Most of this period was characterized by above-average precipitation (Table 1), resulting in soils with high moisture and near field capacity (Supplemental Figure S1). These results indicate that in addition to spring precipitation, above-average winter precipitation can contribute substantially to the total annual drainage. Christianson and Harmel (2015) synthesized results from 91 drainage studies in North America and highlighted the need for a more intensive year-round monitoring to potentially capture drainage during this period, especially considering projected changes in the hydrological cycle as the climate warms (Bowles et al., 2018).

3.2 | Subsurface drainage NO_3–N concentration and loss

Split-N with or without cover crop lost significantly less NO_3–N compared with preplant-N in 2018, and statistically similar to N loss in the control (Table 2). In contrast, annual NO_3–N losses were not significantly different among the fertilized treatments in 2020, ranging from 15.8 (split-N + CC) to 24.1 kg NO_3–N ha^{-1} (split-N). There was no significant difference in annual NO_3–N loss between split-N + CC and control in 2020. When averaged across years, the combination of split-N + CC significantly reduced NO_3–N losses by 37% compared with the preplant-N treatment, but it was not

TABLE 2 Average annual tile drainage discharge volume, nitrate N (NO_3–N) loss, and flow-weighted NO_3–N concentration for each treatment in the 2018–2020 water years[a] and across years

Treatment	2018	2019	2020	Across years (2018–2020)
	Annual drainage volume (mm)			
Preplant-N	389	739	668	599
Split-N	309	735	766	603
Split-N + CC	311	703	766	593
Control	433	613	628	558
Pr > *F*	0.419	0.313	0.379	0.933
	Annual NO_3–N loss (kg ha^{-1})			
Preplant-N	28.6a[b]	32.0	23.7a	26.4a
Split-N	18.1b	29.4	24.1a	22.4ab
Split-N + CC	14.3b	22.2	15.8ab	16.7bc
Control	17.5b	9.3	9.2b	11.4c
Pr > *F*	0.077	0.138	0.100	0.003
	Annual flow-weighted NO_3–N concentration (mg L^{-1})			
Preplant-N	7.8a	4.3	3.4	4.9a
Split-N	6.1ab	4.0	3.5	4.2ab
Split-N + CC	4.5b	3.2	2.2	3.2bc
Control	4.0b	1.6	1.5	2.1c
Pr > *F*	0.045	0.424	0.208	0.001

Note. CC = cover crop.
[a]Water year is defined from 1 Oct. of the previous year to 30 Sept. of that year.
[b]Treatment means within a column followed by different letters are significantly different at $p < .10$ by the Fisher's LSD test.

significantly different from split-N or the control. The preplant-N and split-N resulted in statistically similar NO_3–N losses when assessed over the 3 yr.

Flow-weighted NO_3–N concentration was significantly affected by treatments only in 2018 and across the 3 yr (Table 2). In 2018, flow-weighted NO_3–N concentration was significantly lower with split-N + CC compared with preplant-N but did not differ from the split-N and control. No significant difference between the preplant-N and split-N was also observed in 2018. When averaged across years, flow-weighted NO_3–N concentration was 35% lower with split-N + CC compared with the preplant-N treatment, but it was not statistically different than the split-N and control.

Synchronizing N supply with crop N demand reduces the time that plant-available N can be lost from the soil (Cassman et al., 2002; Robertson & Vitousek, 2009). When comparing the preplant-N and split-N treatments, significant differences in NO_3–N losses were only seen in 2018 (Table 2), which is the year that preplant-N received fall-applied N plus nitrapyrin. The significantly greater loss from the preplant-N treatment was due to high discrete drainage NO_3–N concentrations measured in 2018, especially early in the spring (Supplemental Figure S2). We hypothesize this was due to the warm and wet conditions in late February and early March 2018, which increased the conversion of ammonium to NO_3–N in plots that received fall N. Without plant N uptake during this period, the increased soil NO_3–N concentration was susceptible to leaching losses. Regardless of treatment, ∼50% of the annual NO_3–N loss occurred between February and April 2018 (before preplant-N application and corn planting). By this date, 15.3 and 8 kg NO_3–N ha^{-1} had already been leached through subsurface drainage with preplant-N and split-N, respectively. Although these results are from 1 yr (2018), these findings highlight the potential for loss of fall-applied N followed by wet spring, even when nitrification inhibitor is incorporated (Table 2). Similar findings for increased NO_3–N losses for fall-applied N followed by warm fall and wet spring have been reported by Randall and Vetsch (2005a) in 1 out of 6 yr in Minnesota.

The lack of significant difference in N losses between preplant-N and split-N in WY 2019 and 2020 suggests that splitting N application between preplant and side-dress may not consistently improve water quality outcomes. This may in part depend on when periods of high drainage discharge happened relative to the date of preplant-N application time. Averaged across treatments and WY 2019 and 2020, 82% of the annual drainage and 88% of the annual NO_3–N loss had already occurred by the time of preplant-N application. Moreover, postharvest soil NO_3–N was not significantly different between preplant-N and split-N treatments in the fall of 2018 and 2019 (Supplemental Table S4). Thus, NO_3–N losses were more related to residual soil N and tile flow patterns during the nongrowing season than to N application time. These results indicate that amount of soil N after the growing season and weather conditions during the spring also plays an important role in subsurface NO_3–N losses, and that changes in N application timing alone may not be sufficient to meet reduction targets in the region. Bakhsh et al. (2002) and Randall et al. (2003a) also found no significant differences in annual NO_3–N losses between preplant and split-N application (preplant + side-dress) over a 6-yr and 7-yr study in Iowa and Minnesota, respectively. Similarly, Jaynes (2015) found no significant differences in annual NO_3–N losses when N was applied at the preplant or V6 growth stage.

In contrast to split-N alone, our results showed that the combination of split-N + CC effectively reduced annual flow-weighted NO_3–N concentration and NO_3–N losses compared with preplant-N. Across the 3-yr study period, flow-weighted NO_3–N concentration and NO_3–N loss were reduced by 35 and 37%, respectively (Table 2). Cover crops have often been shown to reduce N losses by 13 to 61% (Kaspar et al., 2007, 2012; Martinez-Feria et al., 2016; Strock et al., 2004). However, no significant difference was found between split-N with or without cover crop in this study, which agrees with previous studies. In a 4-yr study in Iowa, Qi et al. (2011) found that including cereal rye before corn did not reduce flow-weighted NO_3–N concentration nor NO_3–N losses compared with no cover crop when N was applied closely following corn emergence. Similarly, Martinez-Feria (2016) compared split-N application (at planting + side-dress) with and without cover crop and found that cereal rye reduced flow-weighted NO_3–N concentration and NO_3–N losses in 2 of 6 yr in Iowa. Because of the high variability in individual practices, these results help support the premise that a combination of practices will be essential for meeting water quality goals in the Mississippi River basin (Christianson et al., 2018).

It is also important to highlight that notable NO_3–N leaching losses still occurred when no N fertilizer was applied (Table 2). The greater annual NO_3–N loss in 2018 compared with 2019 and 2020 from the control treatment (17.5, 9.3, and 9.2 kg N ha^{-1}, respectively) was mostly due to accumulated residual soil N from the previous year (2017), which was attributed to the combination of high N application rate and below-average precipitation later in the growing season. Corn received 303 kg N ha^{-1} in the 2017 growing season, and despite high grain yields and N removal in portions of the field (Preza Fontes et al., 2019), postharvest soil N was high across all 16 plots, ranging from 27 to 56 kg NO_3–N ha^{-1} (Supplemental Table S4). As discussed above, above-average precipitation during spring 2018 resulted in high soil N losses with drainage discharge. In 2018, 10.3 kg NO_3–N ha^{-1} was lost from the control treatment before the corn growing season, compared with 7.2 kg ha^{-1} lost during the corn growing season. Previous studies have shown similar or greater NO_3–N losses with zero N than those reported here (Helmers et al., 2012; Lawlor et al., 2008; Ruffatti et al., 2019).

TABLE 3 Total aboveground biomass, N concentration, N uptake, and C/N ratio of cereal rye cover crop at termination

Year	Biomass	N concentration	N uptake	C/N ratio
	Mg ha^{-1}	g kg^{-1}	kg ha^{-1}	
2018	0.3	32.3	8.2	12:1
2019	1.2	12.8	15.8	33:1
2020	1.1	18.0	18.1	22:1

3.3 | Cover crop biomass and nitrogen

At cereal rye termination, aboveground biomass was substantially lower in 2018 than in 2019 and 2020 (Table 3). Consequently, the low biomass production resulted in low N uptake and C/N ratio in 2018. Establishing cover crops in the U.S. Midwest can be difficult due to the short period between cash crop harvest and freezing temperatures (Dinnes et al., 2002). In this study, cover crop establishment was greatly affected by unfavorable late-fall growing conditions (cold soils) when cereal rye was drilled after corn harvest in 2017 and 2018 (Table 1). In addition, abnormally low air temperature in March and April resulted in low accumulation of growing degree days and limited cereal rye biomass production in the early spring (March and early April) of both years (Supplemental Figure S3).

The greater aboveground biomass production in 2019 compared with 2018 (Table 3) was attributed to the combination of soil coverage and time of termination. Strip-tillage was done after cover crop planting in WY 2018 but not in 2019. Assuming the soil was disturbed in a 25-cm width zone after fall strip-tillage, the effective soil coverage of cover crop was reduced by ∼33% in 2018. Moreover, wet soil conditions in early-spring 2019 delayed cover crop termination by 3–4 wk. Most of the biomass growth occurred during this period (late April and early May; visually observed but not quantified), with the cereal rye accumulating 43% of the total growing degree days (Supplemental Figure S3). Although N concentration was greater in 2018 than in 2019, total N uptake was 75% lower because of slow growth in early spring. Previous studies have reported similar or greater biomass and N uptake for cereal rye no-till drilled after corn harvest. For instance, cereal rye biomass and N uptake ranged between 0.1 and 2.5 Mg ha^{-1} and 11 and 80 kg N ha^{-1} in separate studies conducted in Iowa (Kaspar et al., 2012; Martinez-Feria et al., 2016; Pantoja et al., 2015) and between 0.5 and 2.7 Mg ha^{-1} and 19 to 67 kg N ha^{-1} in Minnesota, respectively

TABLE 4 Average corn grain yield and yield-scaled nitrate N (NO_3–N) loss for each treatment during 2018, 2019, 2020, and across years

Treatment	2018	2019	2020	Across years (2018–2020)
	Grain yield (Mg ha^{-1})			
Preplant-N	14.8a[a]	12.9a	11.9a	13.2a
Split-N	14.5a	12.4a	12.2a	13.1a
Split-N + CC	14.8a	12.7a	12.1a	13.2a
Control	7.2b	1.7b	1.5b	3.4b
Pr > *F*	<0.001	<0.001	<0.001	<0.001
	Yield-scaled NO_3–N loss (kg N Mg^{-1} grain)			
Preplant-N	2.0a	2.4	2.0	2.1a
Split-N	1.2b	2.3	1.9	1.8ab
Split-N + CC	1.0b	1.7	1.3	1.4b
Control[b]	2.4	9.4	8.2	6.2
Pr > *F*	0.063	0.757	0.440	0.062

Note. CC = cover crop.
[a]Treatment means within a column followed by different letters are significantly different at $p < .10$ by the Fisher's LSD test.
[b]Control treatment was not included in the ANOVA for yield-scaled NO_3–N loss and used only as a reference point when no N was applied. (Refer to Section 2.5).

(Strock et al., 2004). The authors also reported that low cover crop biomass occurred in years with cold weather and short springs.

When weather conditions are favorable for seed germination, broadcasting cover crop into standing corn can lead to early establishment and growth before it gets too cold. In fall 2019, cereal rye seed germinated well because of the 15 mm precipitation within a week after air-seeding into standing corn. Also, warm and wet growing conditions promoted additional biomass growth in early-spring of 2020 (Supplemental Figure S3). In field-scale studies in Minnesota, Wilson et al. (2013) found that precipitation the week after air-seeding into corn and soybean was the most important factor in determining cereal rye establishment. Behnke et al. (2020) reported that biomass production and C/N ratio of cereal rye seeded into standing corn averaged 1.1 Mg ha^{-1} and 15/1 across 5 yr and six locations in Illinois, respectively.

3.4 | Corn grain yield and yield-scaled NO_3–N losses

As expected, grain yield was significantly reduced when no N was applied (control), but it did not differ among the N fertilized treatments within each year or across years (Table 4). In contrast, yield-scaled NO_3–N losses were significantly affected by treatments in 2018 and across years. The preplant-N treatment significantly increased yield-scaled NO_3–N losses compared with the other fertilized treatments in 2018, but not when compared with split-N across years. No significant difference in yield-scaled NO_3–N losses was observed between split-N and split-N + CC in 2018 and across years.

The preplant-N treatment had higher annual NO_3–N losses compared with the other treatments in 2018, but it did not translate to lower yields. It is possible that the favorable growing season resulted in increased mineralization of soil organic matter and soil N supply despite NO_3–N losses in that year. Soil organic matter in this field ranged from 23 to 55 g kg^{-1} (Supplemental Table S2), and the average grain yield and total N uptake (74 kg N ha^{-1}, data not shown) in the control treatment showed that N mineralization supplied substantial amounts of crop N. Previous studies have shown mixed results for N timing impacts on grain yield across the U.S. Midwest. Davies et al. (2020) reported no yield differences among fall, preplant, and split-N applications (at planting + side-dress) in a 3-yr study at Lamberton, MI. In contrast, Randall et al. (2003b) found statistically similar yields between a single fall and preplant-N application, but greater yields with split-N application (preplant + side-dress) across a 7-yr study in Minnesota. Clark et al. (2020) evaluated N application timings on corn production on 49 site-yr across the U.S. Midwest and found that yield differences occurred <15% of the time between preplant and split-N application (preplant + side-dress).

The inclusion of a cereal rye cover crop neither increased nor decreased grain yields in the current study. The net mineralization or immobilization of N is controlled largely by cover crop residue quality (Cabrera et al., 2005). Generally, a C/N ratio <20–40 tends to favor N mineralization rather than immobilization during residue decomposition (Cabrera et al., 2005; Vigil & Kissel, 1991). The C/N ratio of cereal rye was <33:1 in all years (Table 3), and consequently the net immobilization from its residue decomposition was likely minimal. In a litterbag study evaluating biomass degradation and N release, Lacey et al. (2020) reported that ∼45% of the initial N content in cereal rye was released within 40 d after the beginning of the experiment in early May, whereas Pantoja et al. (2016) found a 60% release by 63 d. The C/N ratio of cereal rye was <22:1 in both studies, lower than we measured. In addition, cereal rye was terminated 3–4 wk before corn planting in 2019 and 2020, further reducing the potential for net immobilization early in the growing season. Previous research in Illinois reported that yield reductions are likely to occur when cereal rye is terminated <2 wk before corn planting, especially with >2 Mg ha^{-1} biomass, nearly double the amount in the present study (Crandall et al., 2005).

Expressing NO_3–N losses in relation to crop productivity can help identify management strategies to maintain yields while minimizing environmental pollution. Because grain yields were not different among fertilized treatments, yield-scaled NO_3–N losses followed the same trend as NO_3–N losses, in which split-N + CC significantly reduced yield-scaled NO_3–N losses by ~33% compared with preplant-N across years.

4 | CONCLUSIONS

Three years of subsurface drainage monitoring from large plots (~0.85 ha each) in Illinois showed the combination of split-N application (preplant + side-dress), plus a cereal rye cover crop significantly reduced annual NO_3–N losses by 37% compared with preplant-N application (3-yr average of 16.7 vs. 26.4 kg N ha^{-1}). Average NO_3–N losses were not different between split-N alone (22.4 kg N ha^{-1}) and preplant-N application when assessed over the 3-yr study period. Moreover, we found that corn grain yields were not affected by the timing of N application and cover cropping in any year or when the 3 yr were analyzed together. Understanding potential tradeoffs between crop productivity and water quality is key to increase the adoption of conservation practices by producers in Illinois. Results from this study indicate that combining conservation practices hold more promise for meeting statewide water quality goals without negatively impacting crop productivity.

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AUTHOR CONTRIBUTIONS

Giovani Preza-Fontes: Data curation; Formal analysis; Investigation; Writing-original draft. Cameron M. Pittelkow: Conceptualization; Funding acquisition; Methodology; Writing-review & editing. Kristin D. Greer: Data curation; Project administration; Writing-review & editing. Rabin Bhattarai: Conceptualization; Funding acquisition; Writing-review & editing. Laura Christianson: Conceptualization; Funding acquisition; Methodology; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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