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Split fertilizer nitrogen application with a cereal rye cover crop reduces tile nitrate loads in a corn–soybean rotation

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Abstract

Splitting fertilizer nitrogen (N) applications and using cover crops are management strategies to reduce nitrate in tile drainage water. We investigated split fertilizer N applications to corn (*Zea mays* L.) on crop yields and tile nitrate loss in both corn and soybean (*Glycine max* L.) in rotation from 2016 through 2019. We evaluated the inclusion of cover crops in a split-N treatment. Fertilizer N treatments included 100% in the fall; 50% in the fall + 25% at planting + 25% at side-dress; 100% as spring preplant; 75% as spring preplant (reduced N rate); 50% as spring preplant + 50% at side-dress; and 50% as spring preplant + 50% at side-dress with a cover crop. We did not find significant differences between split and single full rate N application treatments for corn yields or tile nitrate loss; however, the reduced N rate treatment significantly decreased corn yield by 10%. Cumulative tile nitrate losses (over four seasons) ranged from 115 kg ha^{-1} for all of the N in the fall to 65 kg ha^{-1} for 50% as spring preplant + 50% at side-dress with a cover crop, a decrease of 43%. Tile nitrate loss responded similarly to (corn) N treatments under both corn and soybean, with 64% of the loss under corn and 36% under soybean. Our results suggest that decreasing the fertilizer N rate may impact corn yield more than nitrate loss, while split fertilizer N application with a cover crop has potential to reduce tile nitrate loss without decreasing crop yield.

1 | INTRODUCTION

Artificial drainage (dredged ditches and subterranean perforated pipes called tiles) has transformed poorly drained soils (wetlands and prairie marshes) into productive agricultural land and tile installations continue today across the glaciated Midwest United States (Castellano et al., 2019). Tile drainage generally benefits agricultural production by lowering the water table and reducing ponding, quickly shunting water from fields to ditches. This, however, creates a conduit by which nutrients, especially nitrate, can leave the field. Numerous studies have shown how tile drainage transports nitrate from fields to streams (Baker & Johnson, 1981; Christianson & Harmel, 2015; David et al., 1997; Gentry et al., 1998; 2009; Helmers et al., 2012; Jaynes et al., 2001; Kladivko et al., 1991). David et al. (2010) predicted average riverine nitrate-nitrogen (N) yield for all counties in the Mississippi River basin and found that fertilized crops on

Abbreviations: CC, cover crop; F, fall; S, spring; SD, side-dress.

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tile-drained land coincide with the greatest riverine nitrate yields. Split fertilizer N application and cover crops are conservation practices promoted in the Illinois Nutrient Loss Reduction Strategy (Illinois EPA et al., 2015) to reduce N loss; however, the impact of combining these practices on tile water quality is unknown.

Although ammoniacal fertilizers are commonly applied on tile-drained fields, rapid nitrification produces soil nitrate that is susceptible to leaching losses. With corn (*Zea mays* L.) being the predominant row crop receiving fertilizer N in the Midwest United States, determining the appropriate rate and timing of N application is important to minimizing tile nitrate loss. Using a replicated tile drainage study, Pittelkow et al. (2017) found tile nitrate increased with fertilizer N rate and that fertilizer N (ammonia) application in the autumn (fall) ahead of corn production led to greater N loss compared to spring or in-season (side-dress) fertilizer N application. Fall fertilizer N application is a common practice in central Illinois and often accounts for 50% of the total N applied to the state in a given year (Gentry et al., 2014).

Time of fertilizer application is one of the industry's 4Rs of N management (Fixen, 2020) and split application of fertilizer N to corn may enhance the efficiency of fertilizer uptake by improving the synchrony of fertilizer N availability with crop N requirement (Clark et al., 2020; Dinnes et al., 2002; Robertson & Vitousek, 2009). Studies have demonstrated that split application of spring and side-dress fertilizer N can reduce tile nitrate loss (Kanwar et al., 1988; Randall et al., 2003). In contrast, Preza-Fontes et al. (2021) recently concluded that on soil with high silt and clay content, a single N application in a continuous corn cropping system was as effective at maximizing corn yield and minimizing nitrate loss as were split-N applications. However, it is unknown if split-N application reduces tile nitrate loss in a productive Mollisol under a corn–soybean rotation.

Soybean (*Glycine max* L.) is generally rotated with corn in this region and does not receive fertilizer N; however, tile nitrate losses after soybean production can be substantial (David et al., 1997; Waring et al., 2020). Jones et al. (2016) and Villarini et al. (2016) found a positive relationship between soybean acreage and river nitrate in an extensively tile-drained watershed in Iowa. Piske and Pederson (2020) found similar results when evaluating 10 watersheds across the Midwest United States. Understanding the source and timing of nitrate loss following soybean production is critical to reducing tile nitrate loss in a corn–soybean rotation.

Nonleguminous cover crops have been shown to reduce soil inorganic N pools and tile nitrate loss (Dinnes et al., 2002; Ruffatti et al., 2019; Snapp et al., 2005; Strock et al., 2004; Waring et al., 2020). Overwintering grass cover crops have the opportunity to uptake inorganic N during rapid growth in the spring (Krueger et al., 2010). Cereal rye (*Secale cereale*) is a winter hardy cover crop that has been shown to reduce tile nitrate but can decrease soil inorganic N and negatively impact crop yield, especially corn (Crandall et al., 2005; Martinez-Feria et al., 2016). Although split-N application and cover crops are often considered best management practices to reduce tile nitrate loss, we know of no other study that combines both practices to assess tile nitrate loss in a corn–soybean rotation with both phases of the rotation present each year.

Core Ideas

- Tile nitrate loss was measured from adjacent corn and soybean crops in rotation.
- Splitting nitrogen fertilizer on corn did not affect tile nitrate loss or crop grain yield.
- Tile nitrate loss was greater with fall-applied than with spring-applied nitrogen.
- Cereal rye cover crop prior to soybean reduced tile nitrate loss.
- Of total tile nitrate loss, about 64% occurred under corn and 36% under soybean.

We hypothesize that split N application will improve the synchrony of N availability and plant uptake, increasing corn yield and reducing tile nitrate loss in a corn–soybean rotation. Using the same on-farm site as Pittelkow et al. (2017) and building on their findings, this study was designed to test the effect of combining split-N application and cover crops on tile nitrate concentrations, nitrate loads, and crop yields compared to conventional practices such as applying the full rate of fertilizer N in the fall (Gentry et al., 2014). We also evaluated how cover crops within one of the split N application treatments might affect crop yield and nitrate loss. This investigation was initiated during the 2015 water year, which was considered the setup year of the study, and was carried out from 2016 through 2019.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

This field study was conducted on the same private farm in Douglas County, IL, as described by Pittelkow et al. (2017) and Andino et al. (2020). The site is located in the Embarras River watershed within a lacustrine plain dominated by a Milford silty clay loam soil (fine, mixed, superactive, mesic Typic Endoaquolls), characterized as poorly drained with 0%–2% slopes (Soil Survey Staff et al., 2023). In 2016, soil characteristics were determined across the entire research site ($n = 112$)

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(Table S1). Precipitation and air temperature were measured on site using a Davis Instruments Vantage Pro2 Plus weather station. The 30-year (1981–2010) average monthly temperature and precipitation were calculated from daily observations at Tuscola and annual values are expressed on a water-year basis (October 1 of the previous year through September 30 of the named year). The mean annual precipitation at this site is 1041 mm. Temperatures range from a mean daily low of −8.2˚C in January to a mean daily high of 29.7˚C in July. This field contained one of the earliest installed pattern-drained tile systems in the area (Pittelkow et al., 2017). Tiles (12.7 cm in diameter) were installed to an average depth of approximately 1.2 m. Tiles were spaced 30.5 m apart with average lengths of approximately 545 m, creating plots averaging 1.7 ha. Each plot was centered on the tile, and drainage area of each tile was assumed to be the entire plot.

The experimental design accommodated six fertilizer N treatments, arranged in a randomized complete block design with three replicates and both phases of the corn and soybean rotation each year. In central Illinois, fertilizer N may be applied at four distinct times (fall, spring, preplant, at planting, and side-dress) and farmers often use combinations of these times to split their N application. Corn fertilizer N treatments, designated by the percent of the total N that was applied at a given time, included 100% in the fall (100F); 50% in the fall + 25% at planting + 25% as an early side-dress about V3–V5 (50F/25P/25SD; where P is at planting and SD is side-dress); 100% in the spring (S) before planting (100S); 75% in the spring before planting (75S); 50% in the spring before planting + 50% as an early side-dress (50S/50SD); and 50% in the spring before planting + 50% as an early side-dress with a cover crop (CC) seeded the previous fall (50S/50SD CC).

2.2 | Crop management

Following the previous tile drainage study at this site in 2004, the entire study area was planted to either corn or soybean annually in a corn–soybean rotation with corn grown in 2014 at an N rate of 202 kg ha^{-1}. Dividing the study area into both corn and soybean phases in 2015 created second-year corn on half of the study area. Based on the maximum return to N calculator, the recommended N rate for corn after corn (224 kg ha^{-1}) is greater than for corn after soybean in central Illinois (Sawyer et al., 2006). Thus, 2015 was considered a setup year (Table S2).

Crop management variables during the study period (2016–2019), including tillage type, crop planting and harvest dates, crop row spacing, seeding rate, fertilizer N rate, and N application dates, are listed in Table S3. The full corn fertilizer N rate was 179 kg ha^{-1} from 2016 to 2018 and increased to 202 kg ha^{-1} in 2019. Soybean did not receive fertilizer N.

Consistent with common fertilizer application practices in Illinois, type of fertilizer N varied with the time of application. In the fall, anhydrous ammonia was injected 18 cm below the soil surface with an eight-row (0.76 m) Hiniker strip-till bar (Hiniker). The ammonia applicator consisted of a Raven heat exchanger, flow meter, and monitor (Raven Industries). Only fall N application received a nitrification inhibitor (nitrapyrin, N-Serve, Corteva Agriscience) at 0.56 kg a.i. ha^{-1}. In the spring, anhydrous ammonia was injected at 18 cm with a John Deere 3-point mounted bar with a John Deere 2510H low disturbance injection system (Deere & Co.) and a CapstanAG N-ject controller (Topeka). Planting-time applications were made as urea-ammonium nitrate (UAN, 32-0-0) applied with an eight-row Kinze 3000 planter (5.1-cm deep × 5.1 cm from the row). Side-dress applications as UAN were injected 7 cm below the soil surface between the rows using a BueJet AT3000 (Unverferth).

In 2016, phosphorus (P) (0-45-0) and potassium (K) (0-0-60) fertilizers were uniformly applied together at 101 kg ha^{-1} of P and 134 kg ha^{-1} of K based on the Illinois Agronomy Handbook recommendations (University of Illinois, 2021). Herbicides included both a preemergence and a postemergence application each year to each crop. Foliar fungicide was applied to corn following anthesis each year. Crop yields were determined by machine harvesting the center 6.1 m (eight rows) of each plot. Yield was determined using a weigh wagon and moisture meter in the field. Crop grain yields are presented at 15.5% and 13% for corn and soybean, respectively.

2.3 | Cover crop management

In 2015 and 2016, cereal rye was aerially seeded into standing corn (Table S4). Dry conditions and poor germination in the fall of 2016 forced a replant and cereal rye was drill planted (19-cm rows) following corn harvest. In 2017, cereal rye was drill planted following corn harvest and in 2018, it was aerially planted into standing corn (Table S4). Cereal rye was aerially planted at 101 kg ha^{-1} and drill planting at 67 kg ha^{-1}. In the first 2 years of the study, cereal rye was terminated approximately 1 month before soybean planting, whereas in 2018 and 2019, cereal rye was terminated on the day before soybean planting (Table S4). Each year, cereal rye was terminated in the spring by spraying glyphosate (N-(phosphonomethyl)glycine) at 1.29 kg a.i. ha^{-1}. To help manage cover crop residue in 2019, cereal rye was pressed with a roller crimper before spraying glyphosate. Aboveground cereal rye biomass was randomly collected from a 0.25-m^2 area at six locations in each plot prior to termination. Samples were dried at 65˚C for 48 h and weighed. Cover crop biomass was ground and analyzed for N concentration via combustion analysis (A&L Great Lakes Laboratories, Inc.).

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Cover crops such as oat (*Avena sativa*) and radish (*Raphanus sativus*) that winterkill are considered safer to use ahead of corn, but they have much less time in which to grow, especially if dry soils delay emergence. Oat and radish were aerially planted into standing soybean in 2015 and 2016 but failed to establish in either year due to a combination of competition and shading by soybean in narrow rows, interference by leaf litter, and dry conditions, especially in 2016. Oat and radish seed were broadcast after soybean harvest in 2017, but establishment and growth were negligible due to dry conditions that delayed germination. Oat and radish were seeded at 67 kg ha^{-1} and 14 kg ha^{-1} for both aerial and broadcast seeding. Following the repeated failure of the cover crop ahead of corn, we replaced oat and radish with annual ryegrass (*Lolium multiflorum*) in 2018, an overwintering grass that has less aggressive growth in the spring compared to cereal rye. Annual ryegrass was aerially seeded (101 kg ha^{-1}) into standing soybean and establishment was good, but plants were killed by a period of low temperature in January 2019, and there was again no cover crop biomass prior to corn planting in 2019. Therefore, the split-N treatment with cover crop only included a cereal rye cover crop every other year ahead of soybean.

2.4 | Tile monitoring

The 36 individual tiles were monitored for flow by equipping in-line water control structures (Agri Drain, Inc.) with a 45˚ V-notch weir stoplog and determining water height within the structure using a combination pressure transducer and datalogger (Solinst, Inc.). Height of water above the bottom of the weir was logged on 15-min intervals. During flood events, the receiving ditch water submerged the V-notch weir boards and impeded tile flow. Whenever the ditch water increased the water height in the control structure above the height of maximum tile flow (approximately 9 cm above the bottom of the V-notch weir), tile flow was set to zero until water height in the control structures receded. At that point, we assumed a linear increase in tile flow until maximum flow resumed (Li et al., 2020). Water heights above the weir across the 96 logged data points per day were averaged. Daily average flow rate was calculated using a V-notch weir equation as described by Chun and Cooke (2008).

As described in David et al. (2016) and Andino et al. (2020), tile nutrient concentrations were determined from 500 mL water samples collected using automated water samplers (ISCO 3700, Teledyne) at each control structure or via grab samples during periods when air temperatures decreased below 0˚C. Samplers were set to sequential time mode on an 8-h basis to capture nutrient concentration changes during high tile flow events. If no flow events occurred, tile water samples were collected weekly. Tile water samples were collected from automated samplers within 24 h. Samples were vacuum filtered through a 0.45-μm membrane and analyzed for nitrate. Nitrate-N concentrations were measured using ion chromatography (ICS-1600, Dionex) with a minimum detection limit of 0.1 mg N L^{-1}. We used linear interpolation to estimate nitrate concentration for each day between tile sampling dates. Annual tile nitrate loads were calculated by multiplying daily average flow by daily nitrate concentration, expressed on a water year basis. Tile nitrate loads were calculated as cumulative across the 4 years of the study, or as annual averages. Flow-weighted nitrate-N concentrations were calculated by dividing annual tile load by annual discharge. Cumulative flow weighted nitrate-N concentration was calculated by dividing cumulative loads by cumulative tile discharge.

2.5 | Data analysis

Linear mixed effect models fitted by the maximum likelihood (ML) method were employed to assess differences among fertilizer N treatments using the nlme package (Pinhero et al., 2017) in the R statistical software v. 4.2.2 (R Core Development Team, 2017). Preliminary analysis indicated no interaction between year and N treatment; therefore, the dependent variables were a function of N fertilizer treatment and crop as fixed effects and year and block as random effects to evaluate treatment effects across years. Year-by-year effects presented in Supplemental Information Materials were modeled using N treatment, crop, and year as fixed effects and block as a random factor. When necessary, log transformations of the response variables were performed to meet normality assumptions. Subsequently, multiple comparisons of means were evaluated with the Tukey's honestly significant difference procedure with a significance value set at 0.05 using the multcomp package in R (Hothorn et al., 2008).

3 | RESULTS AND DISCUSSION

3.1 | Air temperature, precipitation, and tile discharge

Average monthly air temperature and precipitation deviations from the 30-year mean for each water year are presented in Table S5. Air temperatures during the 2016 and 2017 water years averaged more than 1˚C above the 30-year mean due to warm winter months; February of 2017 was the warmest on record for this area at 6.1˚C above the mean. Air temperatures for the 2018 and 2019 water years were near average, but April 2018 was the second coldest on record and May 2018 was the warmest on record. A polar vortex occurred at the end of January in 2018, decreasing air and soil temperatures

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TABLE 1 Annual mean tile discharge, flow-weighted mean nitrate-N concentration (FWMC), and nitrate-N load by nitrogen (N) treatment under corn and soybean from 2016 to 2019.

	Corn			Soybean		
N treatment	Annual mean tile discharge (mm)	Annual mean NO_3-N FWMC (mg L^{-1})	Annual mean NO_3-N load (kg ha^{-1})	Annual mean discharge (mm)	Annual mean NO_3-N FWMC (mg L^{-1})	Annual mean NO_3-N load (kg ha^{-1})
100F	303a	12.6a	38.9a	315a	6.5a	18.9a
50F/25P/25SD	299a	11.2a	33.9a	315a	6.2a	19.1a
100S	298a	8.6b	26.1b	292a	5.8abc	16.6ab
75S	282a	8.2b	23.1b	304a	4.6cd	13.5bc
50S/50SD	277a	8.3b	23.2b	277a	5.7ab	15.5ab
50S/50SD CC	296a	7.2b	21.5b	311a	3.8d	10.9c

Note: Treatment designations are based on the percent of the full N rate applied at a given time. The full corn fertilizer N rate was 179 kg ha^{-1} from 2016 to 2018 and increased to 202 kg ha^{-1} in 2019. Soybean did not receive fertilizer N. Means not sharing letters are significantly different ($p < 0.05$) according to the Tukey's honestly significant difference test.

Abbreviations: CC, cover crop; F, fall; P, planting; S, spring; SD, side-dress.

to −19.4˚C and −5.9˚C, respectively, prematurely killing the annual ryegrass cover crop, while cereal rye survived.

Annual total precipitation amounts during the water years of 2016, 2018, and 2019 were similar to the 30-year mean, while 2017 precipitation was 171 mm below the 30-year mean (Table S5). Precipitation amounts had the greatest effect on tile discharge in months of low evapotranspiration (generally outside the growing season). Tile flow ceased each summer following a spring surge (Table S6). There were no treatment effects on tile discharge averaged across years or for individual years under corn or soybean (Table 1; Tables S7 and S8). The months of March, April, and May accounted for nearly 50% of the total annual tile discharge. Although the 2017 water year had the least amount of precipitation, large rainfall events in April and May produced the greatest 1-month tile discharge during the study period (89 mm of discharge in May) (Table S6). Regardless of differences in annual precipitation, annual tile discharge during water years 2016, 2017, and 2018 was similar. Precipitation during the 2019 water year was near average; however, the frequency and distribution of precipitation produced the greatest annual tile discharge during the study period (386 mm), equivalent to 37% of the annual precipitation.

Tile nitrate concentrations and loads from this investigation were consistent with other tile monitoring studies conducted in central Illinois (David et al., 1997; Gentry et al., 1998; Gentry et al., 2009; Lemke et al., 2011; Mitchell et al., 2000; Pittelkow et al., 2017; Ruffatti et al., 2019). David et al. (1997) found a close relationship between tile nitrate concentration from a single field in the Upper Embarras River watershed and riverine nitrate concentration, suggesting that tiles are a major source of nitrate to surface waters. Gentry et al. (2014) found the average annual riverine nitrate load was 30 kg N ha^{-1} in the Upper Embarras River watershed from 1993 to 2012. Our research site was located approximately 10 km downstream from the outlet of the Upper Embarras River, providing context for the magnitude of tile nitrate losses found in this study.

3.2 | Cereal rye

Aboveground biomass and N content of the cereal rye cover crop were greatest in 2016 and 2019 due to the warm winter of 2016 and the late termination of cereal rye in 2019 (Table S4). Annual cereal rye biomass (Mg ha^{-1})/biomass N (kg ha^{-1}) were 2.5/31 in 2016, 1.8/25 in 2017, 0.9/22 in 2018, and 2.9/30 in 2019. During the cereal rye growing season, cumulative growing degree days (GDD) base temperature 0˚C were greatest in 2019 (>1600 GDD), whereas <350 GDD were accumulated in 2018. Although there was a positive correlation of aboveground biomass and N content for the cereal rye cover crop ($R^2 = 0.85$), there was a strong inverse correlation between aboveground biomass and N concentration ($R^2 = 0.97$). Cereal rye cover crop biomass of 0.9 Mg ha^{-1} in 2018 contained nearly 70% of the N content of the 2.9 Mg ha^{-1} cover crop biomass in 2019.

3.3 | Tile nitrate losses under corn

Annual mean tile flow weighted mean nitrate concentrations and tile nitrate loads under corn ranged from 7.2 to 12.6 mg NO_3-N L^{-1} and 21.5 to 38.9 kg ha^{-1} (50S/50SD CC vs. 100F) (Table 1). The three-way split-N application with only 50% of the N applied in the fall (50F/25P/25SD) did not significantly reduce annual tile nitrate concentration or nitrate load compared with the single full rate application in the fall (100F) averaged across years under corn (Table 1). Similarly, the two-way split-N application of spring preplant and side-dress applications (50S/50SD) did not significantly reduce tile nitrate concentrations and loads compared with the single full rate application in the spring before planting (100S). Consistent with Clark et al. (2020), our results suggest that split fertilizer N applications to corn on a productive Mollisol do not reduce tile nitrate loss in a corn–soybean rotation.

Tile nitrate concentrations and nitrate loads under corn were significantly greater with fall N application treatments (100F and 50F/25P/25SD) compared with spring N application treatments (Table 1). Numerous studies have investigated the timing of fertilizer N application to corn on tile nitrate loss, especially fertilizer N application in the late fall compared to an application in the spring before corn planting; however, there are varying results in regard to increasing corn yield and decreasing tile nitrate loss (Malzer & Randall, 1985; Pittelkow et al., 2017; Randall & Vetsch, 2005a, 2005b; Touchton et al., 1979; Vetsch et al., 2019). Averaged over 2016–2019, the additional tile nitrate loss under corn (12.8 kg ha^{-1}) resulting from fall N application (100F vs.100S) represented approximately 7% of the fertilizer N applied, and 38% of the annual tile nitrate load (Waring et al., 2020; Welch et al., 1971).

Although fall N application increases the risk of nitrate leaching and tile nitrate loss, it remains a popular practice in central Illinois, primarily to decrease spring workloads and provide earlier corn planting dates (Gentry et al., 2014; Griesheim et al., 2019). In an effort to reduce N losses associated with fall fertilizer N application, current guidelines recommend that producers use a nitrification inhibitor and wait to apply until the soil temperature declines below 10˚C (Illinois Agronomy Handbook). However, similar to Pittelkow et al. (2017), our results clearly show that fall N application (with a nitrification inhibitor) is a major source of nitrate to surface water in intensively tile-drained watersheds in central Illinois.

Mean annual tile flow weighted mean nitrate concentration and tile nitrate load for the reduced N rate treatment (75S) under corn were 8.2 mg L^{-1} and 23.1 kg ha^{-1}. Decreasing the N rate by 25% did not significantly reduce tile nitrate concentration or nitrate load compared to spring application treatments (100S, 50S/50SD, and 50S/50SD CC). Due to the cover crop failure to establish or thrive ahead of corn, the cover crop treatment (50S/50SD CC) did not significantly reduce tile nitrate loss compared with 100S or 50S/50SD. The lack of response of tile nitrate to the 75S treatment following two complete cycles of the corn–soybean rotation may be due to a lag time between accumulation and release of nitrate in shallow groundwater (Williams & McAfee, 2021; Yu et al., 2023).

The greatest tile nitrate concentrations occurred under corn in the 100F treatment as tile nitrate reached >20 mg L^{-1} in 2016, 2017, and 2019, which is more than twice the U.S. EPA drinking water standard for nitrate-N (10 mg L^{-1}). Above-average temperatures, especially in December 2015, occurred throughout the winter and spring months of the 2016 water year, which increased loss from fall N treatments (Figure 1a,b; Table S5). The early application of fertilizer N without a nitrification inhibitor during the unseasonably warm winter temperatures in February 2017 elevated tile nitrate earlier than in other years (Figure 1a) and contributed to greater tile nitrate loads for the 100S compared to the other years (Table S7). In retrospect, it may have been beneficial to use a nitrification inhibitor with the late February N application, or to delay N application. In contrast, the cold spring of 2018, especially April, appeared to limit tile nitrate loss across all N treatments (Figure 1b; Table S7). The period of greatest tile nitrate loss occurred during June–July of 2019 due to a combination of increased tile flow (Table S6) and tile nitrate concentration (Figure 1a). Exacerbated by the late corn planting and limited time for fertilizer uptake, the greatest tile nitrate concentrations found during the study were on June 16, 2019 (27 mg L^{-1} for 100F and 23 mg L^{-1} for 50F/25P/25SD). Of the total tile nitrate load from all N treatments during the study, about 64% occurred under corn, whereas 36% occurred under soybean.

3.4 | Tile nitrate losses under soybean

Mean annual tile flow weighted mean nitrate concentrations and tile nitrate loads under soybean ranged from 3.8 to 6.5 mg L^{-1} (50S/50SD CC vs. 100F) and 10.9 to 19.1 kg ha^{-1} (50S/50SD CC vs. 50F/25P/25SD) (Table 1). Although tile nitrate for the reduced N rate treatment trended lower, the major factor reducing tile nitrate losses under soybean was attributed to the production of the cereal rye cover crop. Except for the cover crop treatment, annual tile nitrate concentration and load under soybean decreased in successive years (Table S8), suggesting a drawdown of nitrate in the shallow groundwater over time.

Cereal rye after corn survived every winter and significantly reduced the mean annual nitrate concentration and nitrate load compared with the other four full N rate treatments during the study period (Table 1). In the first 2 years of the study when tile N losses during the soybean phase were greatest, the warm winter and spring produced a cover crop that significantly decreased tile nitrate compared to 50S/50SD (Table S8). Numerous tile drainage studies show the effectiveness of cereal rye in reducing tile nitrate concentrations (Kaspar et al., 2007, 2012; Ruffatti et al., 2019; Waring et al., 2020). Without a cover crop ahead of corn, there appeared to be a beneficial carryover effect of reduced tile nitrate from the cereal rye cover crop of 2016 on the tile nitrate concentration under corn in 2017 (Figure 1a; Table S7). In 2018, a cold April greatly reduced cereal rye growth (<1 Mg ha^{-1}) and there was no significant effect on tile nitrate. This study demonstrates the direct effect of winter and spring

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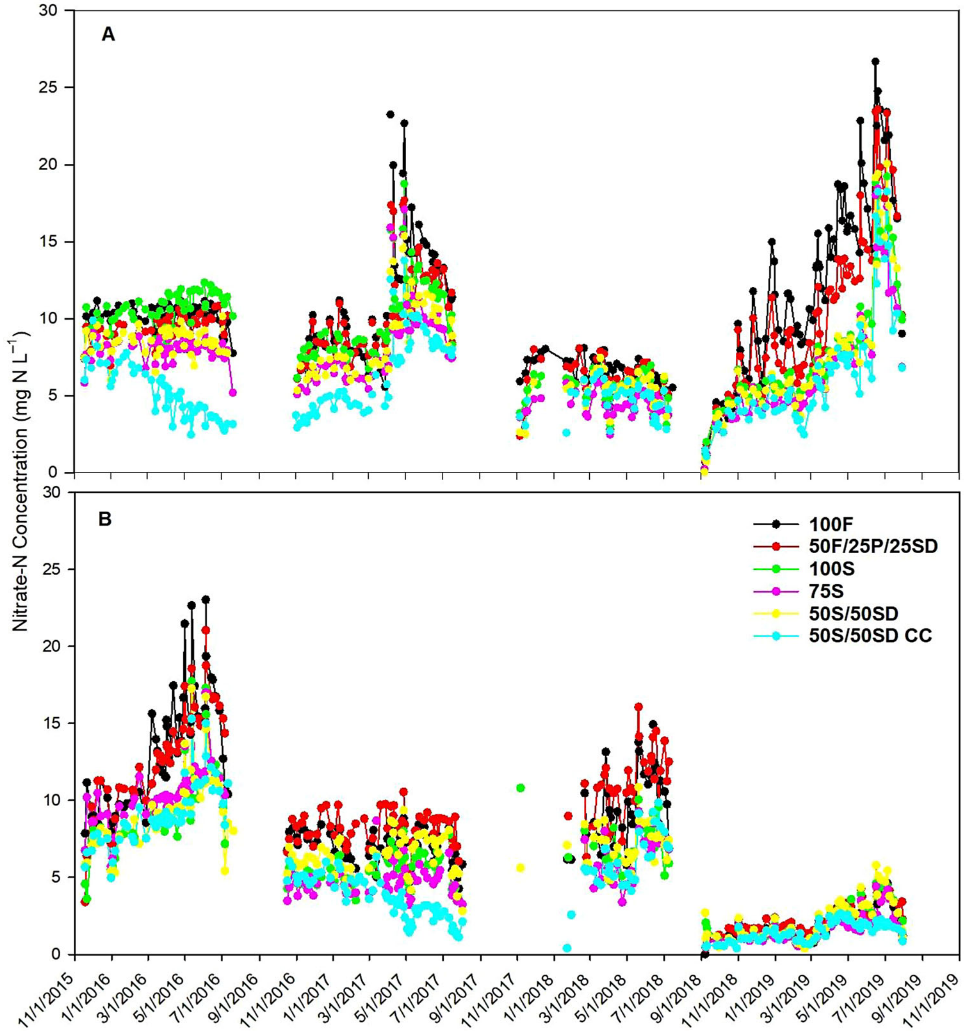

FIGURE 1 Tile nitrate concentrations from six nitrogen (N) treatments under (a) soybean–corn–soybean–corn and (b) corn–soybean–corn–soybean rotation. Nitrogen treatments include: (1) 100% in the autumn season or fall; 100F, (2) 50% in the fall with 25% at planting and 25% as an early side-dress; 50F/25P/25SD, (3) 100% in the spring before planting; 100S, (4) 75% in the spring before planting; 75S, (5) 50% in the spring before planting and 50% as an early side-dress; 50S/50SD, and (6) 50% in the spring before planting and 50% as an early side-dress with a cover crop; 50S/50SD CC. The full corn fertilizer N rate was 179 kg ha^{-1} from 2016 to 2018 and increased to 202 kg ha^{-1} in 2019. Soybean did not receive fertilizer N. Each dot is an average of three replicates.

temperatures on the ability of overwintering cover crops to reduce tile nitrate loss in central Illinois.

3.5 | Cumulative tile nitrate load across corn and soybean

The 4-year cumulative nitrate loads averaged across crop phases for the six fertilizer N treatments range from 65 kg ha^{-1} for 50S/5SD CC to 115 kg ha^{-1} for 100F (Figure 2). Cumulative tile nitrate loads for 50S/50SD and 50S/50SD CC were significantly less than for the two fall N treatments (100F and 50F/25P/25SD). Differences in cumulative tile nitrate load for the split-N application treatments versus the single full N rate application treatments (50F/25P/25SD vs. 100F and 50S/50SD vs. 100S) were not significant. Although 50S/50SD CC lost less tile nitrate than 50S/50SD, this difference was not significant. The reduced rate N treatment (75S) did not significantly reduce cumulative tile nitrate load compared to 100S. Cumulative tile nitrate loads during the study period demonstrate proof of concept that spring split applied N with a cereal rye cover crop every other year ahead of soybean reduced tile nitrate loss by 43% compared to a single full rate application of N in the fall.

3.6 | Corn and soybean yield

The mean annual corn grain yield for all five full fertilizer N rate treatments ranged from 12.5 to 12.9 Mg ha^{-1} (100F vs. 50F/25P/25SD) with no significant difference (Table 2). Only the 75S treatment significantly reduced corn yield

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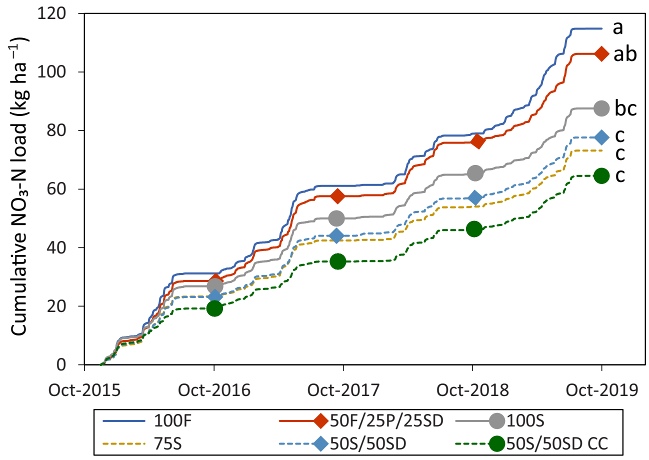

FIGURE 2 Cumulative daily tile nitrate load from the fall of 2015 through the summer of 2019 for each of the six corn nitrogen (N) treatments averaged across corn and soybean. Treatment designations are based on the percent of the full N rate applied at a given time. The full corn fertilizer N rate was 179 kg ha^{-1} from 2016 to 2018 and increased to 202 kg ha^{-1} in 2019. Soybean did not receive fertilizer N. CC, cover crop; F, fall; P, planting; S, spring; SD, side-dress.

TABLE 2 Corn and soybean yield by nitrogen (N) treatment, averaged over 2016–2019.

	Annual mean crop yield	
N treatment	Corn (Mg ha^{-1})	Soybean (Mg ha^{-1})
100F	12.5a	4.6a
50F/25P/25SD	12.9a	4.8a
100S	12.5a	4.6a
75S	11.5b	4.6a
50S/50SD	12.8a	4.7a
50S/50SD CC	12.6a	4.6a

Note: Treatment designations are based on the percent of the full N rate applied at a given time. The full corn fertilizer N rate was 179 kg ha^{-1} from 2016 to 2018 and increased to 202 kg ha^{-1} in 2019. Soybean did not receive fertilizer N. Means not sharing letters are significantly different ($p < 0.05$) according to the Tukey's honestly significant difference test.
Abbreviations: CC, cover crop; F, fall; P, planting; S, spring; SD, side-dress.

by approximately 10%. Corn yields averaged across full N rate treatments were similar to the county grain yield estimates in 2016, 2017, and 2019 (USDA, NASS, 2017). However, in 2018, a year that set a county record of 15.5 Mg ha^{-1}, the average yield of full N rate treatments averaged 17% less. There was no significant treatment effect on corn yield when comparing the split fertilizer N application treatments to the full rate single application treatments (Table 2). Unlike results from studies by Kanwar et al. (1988) and Vetsch et al. (2019) where corn grain yield was enhanced by spring application of N compared to the same rate in the fall, corn grain yield was not significantly affected by the timing of fertilizer N application or by splitting the N application.

Although we could not detect a significant difference in corn grain yield for full N rate treatments, the three-way split N application treatment (50F/25P/25SD) exceeded the other N treatments in 3 of 4 years (Table S9). Without a positive yield response from split N application treatments, the additional field passes and greater cost of UAN (compared to anhydrous ammonia) at planting and/or side-dress would decrease profit margin. Although the 100F treatment lost more tile nitrate than the other treatments, corn grain yield was not significantly reduced, suggesting that soil N mineralization adequately replaced lost N from fall N application.

Mean annual soybean grain yields ranged from 4.6 to 4.8 Mg ha^{-1}. There was no significant treatment effect on soybean grain yield across years or for a given year (Table 2; Table S9). Compared to county estimates, soybean yields were 18% greater in 2016, however, 16% less in 2017 due to dry conditions, and similar in 2018 and 2019 (USDA, NASS). Similar to corn, soybean yields were near record level in 2018. Cereal rye did not significantly affect soybean grain yield in any year even when soybean was seeded directly into standing cereal rye.

Although the reduced N rate treatment produced significantly less corn grain yield compared to the 100S treatment, it did not significantly decrease tile nitrate loss. These data suggest that reducing the fertilizer N rate below the optimal amount will not alone solve the problem of tile nitrate leaching from corn–soybean rotations, largely because substantial amounts of tile nitrate occurred following soybean. Thus, gains in corn N use efficiencies and associated reductions in tile nitrate loss may be masked by tile nitrate loss following soybean production. Cereal rye after corn proved to be effective at decreasing tile nitrate, however, a reliable, winter-hardy cover crop ahead of corn may also help to achieve the goals of reducing tile nitrate in a corn–soybean rotation.

3.7 | Previous crop influences tile nitrate loss

Tile nitrate loss during the nongrowing season demonstrated how the previous row crop can influence tile nitrate concentration and load (Figure S1). To isolate the impact of previous crop on tile nitrate concentrations and loads, we excluded treatments with fall N application and cover crops and ended the evaluation on the day of spring fertilizer N application (Figure S2). During this period (September 28, 2018–May 21, 2019), tile nitrate loads averaged across the three treatments (100S, 75S, and 50S/50SD) were 5 kg ha^{-1} following corn and 18 kg ha^{-1} following soybean. Due to an unusually wet September, tile drainage began early and was continuous through the fall of 2018. The first two tile

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samples collected from a given tile in September had low nitrate concentrations <3 mg L^{-1}, suggesting that crop uptake had reduced soil inorganic N levels (Figure 1a,b). For tiles following corn, nitrate remained <3 mg L^{-1} all winter and modestly increased in the spring. In contrast, for tiles following soybean, nitrate increased to 4 mg L^{-1} in October, steadily increasing through the fall and spring, and reaching 8 mg L^{-1} prior to spring N application. The similarity between the pattern of tile nitrate loss from the reduced rate treatment and the full rate treatments suggest that tile nitrate loss following soybean production had little to do with how much fertilizer N was applied to corn the previous year (Figures S2 and S3). These results support findings by Jones et al. (2016), Villarini et al. (2016), and Piske and Peterson (2020), demonstrating that tile nitrate following soybean production is an important source of tile nitrate, and therefore, river nitrate.

In 2018, corn yields at this site were lower than the county estimate due to N deficiency as indicated by low stalk nitrate concentrations (<50 mg kg) for every corn plot as well as a greater percentage yield reduction for the 75S treatment compared to other years (Table S9). Cold weather in March and April of 2018 may have limited soil N mineralization prior to the growing season, creating a chain reaction of corn N deficiency, increased microbial N immobilization following corn harvest (Gentry et al., 2001; Green & Blackmer, 1995), and decreased tile nitrate loss throughout the drainage season. In accord with findings by McSwiney et al. (2010), N immobilization may play an important role in reducing leaching losses to tile drainage systems.

4 | CONCLUSION

Our results suggest that a single full rate application of anhydrous ammonia in the spring may be considered a best management practice in the productive Mollisols of central Illinois as the more costly split-N application treatments did not significantly decrease tile nitrate loss or increase yield. Our results clearly implicate timing of N fertilization, especially fall N versus spring N application, as a major factor controlling tile nitrate export. We also found that decreasing the fertilizer N rate, from a rate that should be close to optimal, may decrease corn yield more than it decreases nitrate loss, while a cover crop along with a split application of N has potential to reduce tile nitrate loss without decreasing crop yield. Our findings indicate that N mineralization from both soil and crop residues during the nongrowing season, including following soybean production, is an important source of tile nitrate. Moving fall N application to the spring and using overwintering grass cover crops may be the best way to decrease N loss in the intensively tile-drained watersheds of central Illinois.

AUTHOR CONTRIBUTIONS

Lowell E. Gentry: Investigation; writing—original draft. **John M. Green**: Investigation. **Corey A. Mitchell**: Investigation. **Luis F. Andino**: Formal analysis. **Michelle K. Rolf**: Investigation. **D. Schaefer**: Methodology. **Emerson D. Nafziger**: Conceptualization.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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