RESEARCHREPORT
ENVIRONMENT

Title: Drainage Water Quality Impacts of Agricultural Management Practices: Timing of Manure Application and Use of a Winter Cereal Rye Cover Crop - #**18-134 IPPA**

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Industry Summary

Agricultural nutrient management practices are an important component of on farm efforts to improve profitability and reduce environmental impacts. Incorporating cover crops into existing crop rotations is one way to reduce nutrient losses from the field. Previous research has shown that cover crops are generally effective for reducing nitrate-N losses from subsurface drainage systems. Using cover crops together with manure has the potential to provide synergetic benefits to soil and cropping systems, as shown in Figure 1.

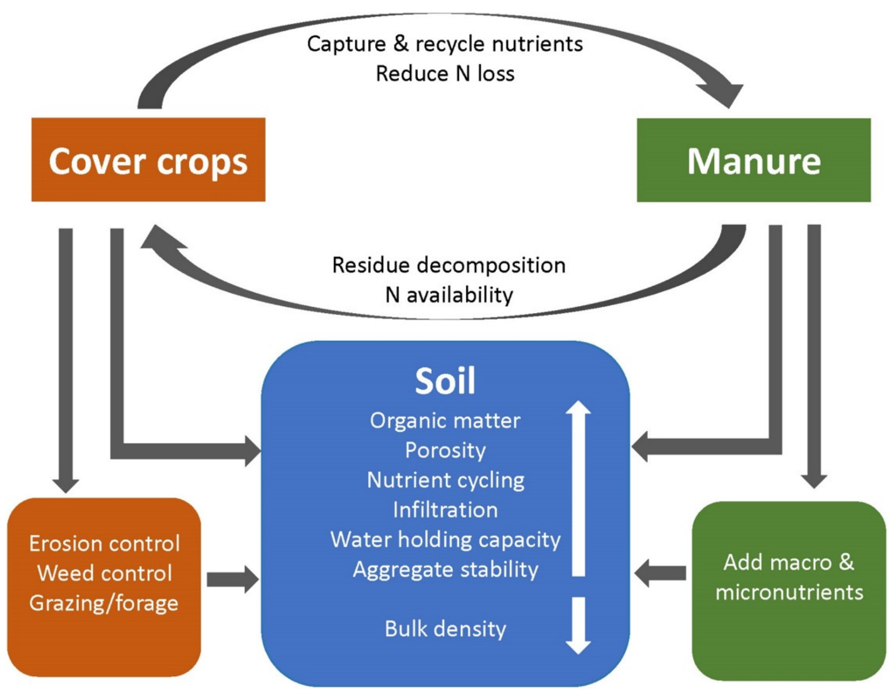

Figure 1. Schematic showing how manure and cover crops can be mutually beneficial in cropping systems.

However, questions remain as environmental performance and crop yields in systems where cover crops and manure are used together. Due to manure storage capacity issues, weather, and other factors, some manure is typically fall-applied before soils have cooled to below 50°F. This is the point at which soil biological activity slows considerably and there is less risk of N being lost before it is taken up by the following crop. This research explores whether a cereal rye cover crop can mitigate the negative effects of early-fall applied manure.

Nitrification inhibitors are another option for trying to better match the timing of nutrient availability to nutrient demand by the crop. These inhibitors work by delaying the conversion of ammonium-N to nitrate-N, but the water quality benefits from nitrification inhibitors used with fall manure are uncertain. Gypsum soil amendments have also been used to try to reduce the loss of dissolved P through subsurface drainage. This is a significant concern in areas near the Great Lakes, but the effectiveness of gypsum for P loss reduction in Iowa has not been evaluated.

A four-year study was started in the fall of 2015 at the Northeast Research Farm near Nashua, Iowa to evaluate these techniques. The objectives of the study were to evaluate the effects of liquid swine manure application timing, cereal rye cover crops, Instinct® II nitrification inhibitor, and a gypsum soil amendment on grain yields and on nitrate-N and Total Reactive Phosphorus (TRP) losses via subsurface drainage. The research was done on thirty-six 1-acre plots outfitted with a subsurface drainage water quality monitoring system. Treatments included Early Fall Manure (EFM) with and without a cereal rye cover crop and Late Fall Manure (LFM). These plots were managed as no-till corn-soybean rotations and received 150 lb N ac^{-1} from liquid swine manure. The EFM was applied as soon as possible after harvest, whereas the LFM was applied after soils had cooled to below 50°F. There was also a spring urea-ammonium nitrate (UAN) treatment that received 150 lb N ac^{-1} from UAN as a sidedress application. Additional treatments were managed with tillage in a continuous corn system. These included LFM, LFM with Instinct® nitrification inhibitor, LFM with gypsum applied every other year at 1 ton ac^{-1}, and Spring Manure (SM). These plots received 200 lb N ac^{-1} from liquid swine manure.

Results showed that EFM with a rye cover crop resulted in significantly lower 4-yr average nitrate-N concentrations in drainage water and compared to EFM without a cover crop in both corn and soybeans. Four-yr average N uptake in aboveground cereal rye biomass averaged 88 lb N ac^{-1} prior to corn and 61 lb N ac^{-1} prior to soybeans, suggesting that significant recycling of both residual soil nitrate-N and manure N occurred. There were no significant differences in 4-yr average nitrate-N concentrations or N losses in continuous corn treatments receiving either LFM or SM. Average TRP concentrations ranged from 7 to 40 µg P L^{-1} and there were no significant differences between treatments. The nitrification inhibitor showed promise for improving yields when applied with fall manure but it had no detectable effect on water quality. Biennial fall applications 1 ton ac^{-1} of gypsum had no observable effects on water quality or yields. Delaying manure applications from early fall to late fall resulted in a 40 bu ac^{-1} advantage in rotated corn yield averaged over 3 years. Delaying manure application from late fall to spring resulted in a 38 bu ac^{-1} yield advantage in continuous corn averaged over 3 years. Due to adverse weather conditions, manure applications were delayed for the 2019 cropping season. In rotated corn, LFM with a cover crop out-yielded LFM with no cover crop by 14 bu ac^{-1}, and SM out-yielded LFM by 18 bu ac^{-1} in 2019.

These results show that the cereal rye cover crop provided significant water quality benefits and did not affect average corn yields. Cover crop N uptake was substantial in an early fall manure system.

This recycling of N by the cover crop led to a reduction in N loss via the drainage system, and the yields observed in this study suggest that the cover crop works well with fall-applied manure, especially if that manure is applied before soils have cooled to below 50°F. The results also indicate that delaying manure application so that it was applied closer to the period of crop nutrient demand resulted in significant corn yield increases.

The data from this study indicates that delaying fall manure applications until soils have cooled to below 50°F can help to protect water quality and enhance yields. If fall manure must be applied earlier, including a cover crop can help mitigate N loss to the environment. While application in the spring presents logistical challenges and potential for compaction if soils are wet, yield data suggests that the economic benefit might justify moving to a spring pre-plant or side-dress manure application system where feasible.

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Key Findings

- A cereal rye cover crop provided significant water quality benefits and did not affect average corn yields.
- Cover crop N uptake was substantial in an early fall manure system.
- Delaying manure application to better match crop nutrient demand resulted in significant corn yield increases.

Keywords: Cover crop, Nitrate-N leaching, Total Reactive Phosphorus, manure timing, nitrification inhibitor.

Abstract

Agricultural nutrient management practices are an important component of the effort to improve water quality in the Mississippi River Basin. Optimizing the use of fertilizers and animal manures in combination with other management practices has the potential to minimize negative impacts on water quality. The objectives of this study are to evaluate the effects of liquid swine manure application timing, cereal rye (*Secale cereale*) cover crops, a nitrification inhibitor, and gypsum soil amendment on grain yields and on nitrate-N and Total Reactive Phosphorus (TRP) losses via subsurface drainage. The study was evaluated from 2016 through 2019 using thirty-six 0.4 ha (1 ac) plots outfitted with a subsurface drainage water quality monitoring system.

Results show that early fall applied swine manure (EFM) with a rye cover crop resulted in significantly lower 4-yr average nitrate-N concentrations in drainage water compared to EFM without a cover crop in a corn (*Zea mays* L.) - soybean (*Glycine max* (L.) Merr.) rotation. Four-yr average N uptake in aboveground cereal rye biomass averaged 98 kg N ha^{-1} (88 lb N ac^{-1}) prior to corn and 68 kg N ha^{-1} (61 lb N ac^{-1}) prior to soybeans, suggesting that significant recycling of both residual soil nitrate-N and manure N occurred. There were no significant differences in 4-yr average nitrate-N concentrations or losses in continuous corn treatments receiving either LFM or spring manure (SM). Average TRP concentrations were low (7 to 40 µg P L^{-1}) and there were no significant differences between treatments. The Instinct® nitrification inhibitor showed promise for improving yields when applied with fall manure but it had no detectable effect on water quality. Biennial fall applications of

2.24 Mg ha^{-1} (1 ton ac^{-1}) of gypsum had no observable effects on water quality or yields. Delaying manure applications from both early fall to late fall and from late fall to spring resulted in significant increases in corn yield.

Introduction

Water table management through the use of artificial subsurface drainage systems has resulted in very productive lands in humid zones with naturally poorly or somewhat naturally poorly drained soils. Subsurface drainage systems were predominately installed at the end of the 19th and during the first half of the 20th century and were necessary in the conversion of the prairie-wetlands landscape into agricultural production areas. Excess precipitation in these converted landscapes in Iowa and other corn and soybean belt states in the Upper Mississippi/Ohio River watershed agricultural production states is removed artificially via subsurface drainage systems that intercept and divert it to surface waters. Agricultural drainage systems have been installed to allow timely seedbed preparation, planting and harvesting, and to protect crops from extended periods of flooded soil and/or high water table conditions. In general, improved subsurface drainage also results in less surface runoff. Surface runoff normally has higher concentrations of sediment, phosphorus, ammonium-nitrogen (NH4-N), bacteria, and some pesticides than does subsurface drainage. The tradeoff for improved subsurface drainage is a significant increase in nitrate-nitrogen (nitrate-N) leaching loss (Gilliam et al., 1999).

A 2012 Census of Agriculture survey indicates that Illinois, Indiana, Iowa, Ohio, and Minnesota have a total of nearly 38.7 million hectares (95.5 million acres) of agricultural land with artificial subsurface drainage, which represents approximately 40% of total cropland (USDA NASS, 2014). Nitrogen, either applied as fertilizer, manure or derived from soil organic matter, can be carried as nitrate-N with the excess water in quantities that may have deleterious effects downstream. The movement of N from agricultural fields via subsurface drainage waters is a major factor in nonpoint source pollution of surface waters and ultimately the Gulf of Mexico, where it has been implicated as a primary contributor to the hypoxic zone (Rabalais et al., 1996; Mitsch et al., 2001). The environmental impacts of subsurface drainage depend on the agronomic practices implemented, as well as site, soils, and climatological factors.

Liquid swine manure is an important crop nutrient resource for Iowa farmers. Due to logistical reasons producers may apply the liquid swine manure at a variety of times including early in the fall before soils are 10°C (50°F) and cooling. This practice is commonly mentioned as potentially risky relative to water quality but there have not been any studies that have studied this early manure application. With the increasing interest in use of winter cereal rye cover crop there may be the potential to combine the use of a cover crop with the early manure application to mitigate any potential water quality risk. Another factor relative to early manure application is potential impact on crop yield. If there is an increased risk of nitrogen loss there may be less nitrogen within the soil profile to supply crop needs. As a result, it is important to not only investigate water quality impacts but also crop yield impacts.

In cropping systems where corn is planted two or more consecutive times and manure is applied every year to supply nitrogen needs for the corn crop the phosphorus applied with the manure often is higher than required or removed with harvest. This increases soil test phosphorus levels over time, which previous information indicates may increase dissolved phosphorus loss in subsurface drainage. In some parts of the Midwest the use of gypsum application at rates much higher than needed to supply sulfur for crops (one to two tons per acre) is being considered or recommended for reducing the risk of dissolved phosphorus loss in drainage. However, there is conflicting information to justify this practice even in those regions and there is a need for evaluating this practice under Iowa conditions.

Corn and soybean producers in Iowa are increasingly challenged to maximize crop production to supply feed, fiber, and more recently biofuels, while at the same time managing soils by utilizing fertilizers and animal manures efficiently to minimize negative impacts on water quality. In particular, there is concern about nutrient export with subsurface drainage and surface water runoff to surface water systems in Iowa and the Gulf of Mexico. Nitrate loss through subsurface drainage systems is of primary concern but there are also concerns about dissolved phosphorus loss through drainage systems. With the extensive use of liquid swine manure in Iowa there is a need for water quality and crop yield evaluation of the timing of the manure application as well as use of products or practices that may have the potential to reduce nutrient loss.

Objectives

The overall the objectives of the proposed study are to evaluate the impacts of various cropping and nutrient management systems subsurface drainage water quality and crop yields. Specific objectives were to evaluate the concentrations of nitrate-N and TRP in subsurface drainage water and crop yields resulting from (i) early fall vs. late fall vs. spring applied liquid swine manure (ii) use of a cover crop with early fall liquid swine manure (iii) use of a nitrification inhibitor, and (iv) use of a high application rate of gypsum soil amendment.

Materials & Methods

Site Description

Experimental data was collected at the Iowa State University Northeast Research and Demonstration Farm near Nashua, IA. The soils at the site include Floyd loam (fine-loamy, mixed, mesic Aquic Hapludolls), Kenyon loam (fine-loamy, mixed, mesic Typic Hapludolls), and Readlyn loam (fine-loamy, mixed, mesic Aquic Hapludolls) (Kanwar et al., 1997). The Kenyon soil is classified as moderately well drained whereas the Floyd and Readlyn soils are moderately poorly drained. These soils, particularly Floyd and Readlyn, have a seasonally high water table and benefit from subsurface drainage. Subsurface drains were installed in thirty-six 0.4 ha (1 acre) plots in 1979, several years prior to the study. Each of the plots was drained separately via subsurface drain lines installed in the center of each plot at a depth of 1.2 m (4 ft) below the ground surface with a drain spacing of 28.5 m (94 ft). Subsurface drainage cross-flow from one plot to another was minimized by installing drainage lines between plot borders and isolating the plots with berms (Kanwar et al., 1999). In 1988, the central subsurface drainage lines were intercepted at the downslope end of the plots and were connected to individual sumps for measuring drainage effluent and collecting water samples for chemical analysis. The sumps were equipped with a 110-volt effluent pump, water flow meter, and an orifice tube located on the discharge pipe of the sump pump. Approximately 0.2% of the water pumped from the sump flowed through the 5-mm diameter polyethylene orifice tube to a water sampling bottle located in the collection sump each time the pump emptied the sump water. A more detailed description of the subsurface drainage system can be found in Kanwar et al. (1999).

Experimental Design and Treatments

The experiment was established in 2015 using a randomized complete block design with eight different treatments and three replications (blocks). Treatment details are shown in Table 1. Treatment abbreviations are: EFM = Early Fall Manure, LFM = Late Fall Manure, SM = Spring Manure, SU = Spring UAN, NT = No-Till, +G = Gypsum application, +I = Instinct® II (nitrapyrin) nitrification inhibitor, and +R = Rye cover crop. The target N application rate in lb N ac^{-1} for each treatment is also given in the abbreviation. Four of the treatments were planted to CC, with three replicates each of LFM200, LFM200+G, LFM200+I, and SM200. All other treatments were managed with a CS rotation with both crops of the rotation present each year. For treatments managed with tillage, the plots with corn residue were chisel plowed in the fall after corn harvest and all corn and soybean plots were field cultivated in the spring before planting the crops.

Table 1. Experimental treatments for the 2016 through 2019 water quality study at the ISU Northeast Research Farm, Nashua, IA.

Treatment	Timing and source of N	N Rate, lb ac^{-1}	Crop rotation	Tillage
EFM150NT	Early Fall Manure	150 -	Corn Soybean	No-Till No-Till
EFM150NT+R	Early Fall Manure	150 -	Corn + Rye cover Soybean + Rye cover	No-Till No-Till
LFM150NT	Late Fall Manure	150 -	Corn Soybean	No-Till No-Till
SU150	Spring UAN	150 -	Corn Soybean	Chisel plow corn fall Field cultivate both spring
LFM200	Late Fall Manure	200	Continuous corn	Chisel plow fall Field cultivate spring
LFM200+I	Late Fall Manure + Instinct	200	Continuous corn	Chisel plow fall Field cultivate spring
LFM200+G	Late Fall Manure + Gypsum	200	Continuous corn	Chisel plow fall Field cultivate spring
SM200	Spring Manure	200	Continuous corn	Chisel plow fall Field cultivate spring

Liquid swine manure was obtained from a growing-finishing swine facility. Manure application rates were estimated with an initial sampling from the manure pit and the actual N, P, and K application rates were determined with manure samples taken from the agitated manure application tank the day the manure was applied. The manure was applied via injection with 76 cm (30 in) spacing to a depth of approximately 15 cm (6 in). Early fall manure was applied as soon as was feasible after fall soybean harvest. Late fall manure was applied after soils had cooled to below 10°C. The Instinct® II nitrification inhibitor used in FM200+I was blended into the manure with the manure tanker agitation pump and applied at a rate of 5.1 L ha^{-1} (0.55 gal ac^{-1}). Spring manure was applied when conditions were suitable prior to planting. The SU150 treatment received spring applications of 32% urea ammonium nitrate solution (UAN) at a target rate of 150 lb N ac^{-1} approximately three weeks after corn was planted. The UAN was injected to a depth of approximately 15 cm (6 in) behind a fluted coulter blade in the center of every second row of corn. The FM200+G treatment received a single application of gypsum (23% Ca, 17% S) at 2.24 Mg ha^{-1} (1 ton ac^{-1}) in the fall of 2015 and 2017. Elbon variety cereal rye was drill seeded immediately after harvest in 200 mm (7.5 in) rows at a rate of 90 kg ha^{-1} (80 lb ac^{-1}).

Soil, Plant, and Drainage Sampling

Cumulative subsurface drain flows were recorded and integrated water quality samples were collected for nutrient analysis once per week from late February or early March to the beginning of December during the study period. The drainage water samples were analyzed for nitrate-N and Total Reactive Phosphorus (TRP) with a Seal Analytical AQ2 Discrete Analyzer (Mequon, WI). The minimum standard for nitrate-N was 0.012 mg N L^{-1} with a detection limit of 0.003 mg N L^{-1}. For TRP the minimum standard and detection limits were 0.01 and 0.002 mg P L^{-1}, respectively. Samples were stored at 4˚C prior to analyses and were not filtered since no turbidity was observed.

Cereal rye was sampled to quantify dry biomass and total N, P, and K in aboveground plant material each spring prior to termination with glyphosate. Sampling took place in four random 0.5 m^2 locations in each rye plot, with four samples taken between the manure injection band and four samples directly over the manure injection band. Grain yields were determined by averaging three yield check strips from each plot. Grain yields were adjusted to a moisture content of 15% for corn and 13% for soybeans. Grain, corn stover, and cereal rye plant samples were analyzed for total N, P, and K on a mass basis (Zarcinas et al., 1987).

Data Management and Statistical Analysis

Subsurface drainage flow in depth units for each replicate was calculated by dividing total flow volume by drainage area. The annual nitrate-N and TRP loss via subsurface drainage water in kg ha^{-1} was calculated by multiplying the concentrations in mg L^{-1} with the drainage flow depth in cm and dividing it by 10 for each interval of sampling. Quarterly and annual flow-weighted nitrate-N and TRP concentrations were calculated by multiplying the total mass loss from each replicate for a given period by 10 and dividing by total drainage depth (cm) from that same period. In the CS rotations, data from the three replicates of each crop and treatment were averaged to determine the overall value for each crop, and data from all six plots were averaged to determine the overall treatment effect for the rotation. Statistical analysis was done with SAS™ software version 9.4 (SAS Institute, 2015). All statistical comparisons were done using PROC GLM assuming fixed block and treatment effects. Comparisons among treatments were tested at 5% significance level using the Least Significant Difference (LSD) method only when the treatments main effect was significant at $P \leq 0.05$.

Results

Precipitation

Table 2 gives the monthly precipitation for the 2016 through 2019 growing seasons. Precipitation was much greater than the 30-yr average for both 2016 and 2018. Growing season precipitation in 2018 was the wettest since recordkeeping began at the farm in 1976. Total precipitation in both 2017 and 2019 was close to the 30-yr average at the research farm.

Table 2. Precipitation (inches) during the 2016 through 2019 growing seasons.

	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Total
2016	2.34	3.04	11.62	6.05	7.32	14.91	2.32	1.32	48.92
2017	4.31	4.79	5.15	8.35	1.75	2.25	4.86	0.37	31.83
2018	2.81	6.26	9.73	2.9	10.2	14.58	3.78	2.03	52.29
2019	3.77	6.32	2.89	3.46	2.50	3.94	5.20	2.15	30.23
1986-2015 avg.	3.88	4.44	5.40	4.75	4.37	2.64	2.47	1.75	29.70

Water quality

Table 3 shows annual and 4-yr average flow-weighted nitrate-N concentrations in drainage water for 2016 through 2019. In the corn phase of corn-soybean plots, the early fall manure treatment with no cover crop had significantly higher 4-yr average nitrate-N concentrations compared to the other treatments. The cover crop led to significantly lower nitrate-N concentrations in three out of the four years in the corn phase. In the soybean phase the cover crop treatment had significantly lower concentrations in all years compared to the other treatments. There were minimal differences in nitrate-N concentrations in the continuous corn plots. The nitrification inhibitor did not reduce nitrate-N concentrations compared with no inhibitor and the gypsum application did not reduce nitrate-N concentrations compared with no gypsum.

Table 3. Annual flow-weighted nitrate-N concentrations in mg L^{-1} for 2016 through 2019.

System	SU 150	EFM 150NT	EFM 150NT+R	LFM 150NT	SU 150	EFM 150NT	EFM 150NT+R	LFM 150NT	LFM 200+I	SM 200	LFM 200	LFM 200+G
Crop	Corn	Corn	Corn	Corn	Soy	Soy	Soy	Soy	CC	CC	CC	CC
	Flow weighted nitrate-N concentration, mg L^{-1}											
2016	12.0c	20.5a	11.3c	15.7b	11.4a	10.9a	6.7b	12.0a	21.6a	22.0a	21.1a	20.7a
2017	13.2c	27.2a	12.0c	20.1b	12.6a	9.5ab	4.9c	8.7b	18.3a	14.7b	17.1a	18.2a
2018	10.5a	12.3a	11.9a	11.2a	9.5a	7.2bc	5.6c	8.3ab	10.9a	9.4a	11.0a	9.8a
2019	11.2b	21.5a	14.1b	11.8b	10.8a	7.5b	7.6b	7.5b	10.7a	10.3a	9.4a	10.8a
4-yr Avg	**11.7b**	**20.4a**	**12.3b**	**14.7b**	**11.1a**	**8.8b**	**6.2c**	**9.1b**	**15.4a**	**14.1a**	**14.6a**	**14.9a**

Concentrations with the same letter within year are not significantly different at P = 0.05. Corn, soybean, and continuous corn were evaluated separately.

Table 4 shows 4-yr (2016 – 2019) average quarterly flow-weighted nitrate-N concentrations in drainage water. There was no flow in January and minimal flow in February due to frozen soil conditions. In the corn phase of corn-soybean plots, EFM150NT had significantly higher nitrate-N concentrations compared to the other treatments in the first 2 quarters of the year. In soybeans, EFM150NT+R had significantly lower concentrations from April through December. On a quarterly basis there were no significant differences in the continuous corn treatments. Nitrate-N concentrations peaked in the second quarter in all treatments except the cover crop treatment in soybeans.

Table 4. Quarterly flow-weighted nitrate-N concentrations averaged over four years (2016-2019) in mg L^{-1}.

System	SU 150	EFM 150NT	EFM 150NT+R	LFM 150NT	SU 150	EFM 150NT	EFM 150NT+R	LFM 150NT	LFM 200+I	SM 200	LFM 200	LFM 200+G
Crop	Corn	Corn	Corn	Corn	Soy	Soy	Soy	Soy	CC	CC	CC	CC
	Flow weighted nitrate-N concentration, mg L^{-1}											
Jan-Mar	9.1b	19.8a	12.9b	11.4b	11.7a	9.2a	7.8a	9.9a	18.3a	13.9a	14.7a	16.1a
Apr-Jun	13.4c	26.4a	17.0bc	19.0b	14.0a	10.5b	7.4c	10.7b	19.5a	16.6a	19.1a	21.6a
Jul-Sep	11.3bc	15.8a	10.5c	14.0ab	8.9a	7.3a	5.3b	8.0a	14.5a	13.8a	13.1a	12.4a
Oct-Dec	8.3ab	9.3a	4.9b	9.3a	7.1a	7.1a	5.2b	7.1a	9.1a	7.4a	9.1a	5.4a

Concentrations with the same letter within quarter are not significantly different at P = 0.05. Corn, soybean, and continuous corn were evaluated separately.

Annual and 4-yr avg N losses in lb ac^{-1} are shown in Table 5. Losses in 2016 and 2018 were higher than the other years due to significantly greater than average rainfall and subsequent drainage flow (data not shown) in those years. Considerable plot-to-plot variability in drainage flows was seen due to historical tillage practices (affecting infiltration rates) and natural soil variability across the site. This makes it difficult to detect statistical differences between treatments in spite of relatively large differences in N loss. The cover crop appeared to reduce total N loss in both corn and soybeans, but the difference was not statistically significant.

Table 5. Annual and 4-yr average nitrate-N losses in lb ac^{-1} for 2016 through 2019.

System	SU 150	EFM 150NT	EFM 150NT+R	LFM 150NT	SU 150	EFM 150NT	EFM 150NT+R	LFM 150NT	LFM 200+I	SM 200	LFM 200	LFM 200+G
Crop	Corn	Corn	Corn	Corn	Soy	Soy	Soy	Soy	CC	CC	CC	CC
	Nitrate-N losses, lb ac^{-1}											
2016	29.5b	72.5a	40.9ab	60.0ab	25.8ab	31.9ab	21.0b	51.0a	59.5a	61.6a	70.5a	62.4a
2017	17.8b	38.5ab	20.6ab	51.6a	17.3a	31.1a	14.3a	28.5a	34.9a	23.7a	36.0a	34.3a
2018	30.3a	58.7a	46.1a	46.2a	26.2a	19.1a	18.8a	37.1a	43.2a	37.1a	43.7a	33.0a
2019	5.7a	11.2a	8.1a	14.5a	5.4a	13.5a	10.4a	11.8a	7.9a	6.3a	7.9a	7.0a
4-yr Avg	**20.9b**	**45.2a**	**28.9ab**	**43.1a**	**18.7b**	**23.9ab**	**16.1b**	**32.1a**	**36.4a**	**32.2a**	**39.5a**	**34.2a**

Losses with the same letter within year are not significantly different at P = 0.05. Corn, soybean, and continuous corn were evaluated separately.

Table 6 shows the annual average flow-weighted TRP concentrations in drainage water for 2016 through 2019. In 2016, annual average TRP concentrations ranged from 4 to 27 µg L^{-1}. In 2017 concentrations ranged from 3 to 29 µg L^{-1}. Concentrations in 2018 ranged from 6 to 33 µg L^{-1}. There were no statistically significant differences between any of the systems on an annual basis. Averaged over 4 years, there was a significant difference between treatments in the soybean phase of the corn-soybean rotations. However, it should be noted that these concentrations are very low (1 µg equals 0.001 mg) and may of the TRP results were below the detection limit of the analysis equipment. The results suggest that none of the treatments had a significant effect on TRP leaching. The low concentrations show that there is minimal TRP leaching at this location.

Table 6. Annual flow-weighted Total Reactive Phosphorus (TRP) concentrations in ug L^{-1} for 2016 through 2019.

System	SU 150	EFM 150NT	EFM 150NT+R	LFM 150NT	SU 150	EFM 150NT	EFM 150NT+R	LFM 150NT	LFM 200+I	SM 200	LFM 200	LFM 200+G
Crop	Corn	Corn	Corn	Corn	Soy	Soy	Soy	Soy	CC	CC	CC	CC
	Flow weighted TRP concentration, ug L^{-1}											
2016	9a	7a	11a	9a	4a	27a	5a	17a	8a	6a	10a	16a
2017	4a	29a	4a	5a	5a	3a	7a	5a	4a	5a	7a	7a
2018	6a	10a	11a	11a	9a	30a	13a	9a	10a	8a	36a	33a
2019	42a	46a	26a	23a	9a	20a	24a	17a	42b	36b	107a	105a
Average	**15a**	**23a**	**13a**	**12a**	**7b**	**20a**	**12ab**	**12ab**	**16a**	**14a**	**40a**	**40a**

Concentrations with the same letter within year are not significantly different at P = 0.05. Corn, soybean, and continuous corn were evaluated separately.

Cover crop growth

Spring rye cover crop biomass, nutrient uptake, and planting and sampling dates for 2016 through 2019 crop years are shown in Table 7. Rye biomass was sampled in and between the swine manure injection bands in the soybean residue plots in 2016 through 2018. Uptake of N, P and K was considerably greater in the manure injection bands compared to between the injection bands in those three years.

Four-yr average N uptake in aboveground biomass averaged about 98 kg N ha^{-1} (88 lb N ac^{-1}) prior to corn and 68 kg N ha^{-1} (61 lb ac^{-1}) prior to soybeans. Biomass growth and nutrient uptake in 2019 did not differ between manured plots and those receiving no manure, possibly due to late application of manure and no cover crop growth in the fall of 2018.

Table 7. Cereal rye cover crop aboveground biomass and N, P, and K uptake.

Residue	Plant date	Sample date	Sample location	Biomass, Dry lb ac^{-1}	N %	P %	K %	N lb ac^{-1}	P lb ac^{-1}	K lb ac^{-1}
Soybean	10/7/15	4/14/16	In-band	2548	4.72	0.51	3.25	120.4	12.9	83.1
Soybean			Between band	826	4.02	0.33	2.50	33.3	2.8	20.6
Corn	10/21/15	4/25/16	-	1526	2.74	0.27	2.55	42.0	4.2	39.3
Soybean	10/10/16	4/17/17	In band	2490	4.48	0.49	3.81	111.1	12.4	95.6
Soybean			Between band	1117	4.18	0.43	3.43	46.9	4.8	38.6
Corn			-	1559	3.05	0.37	2.82	49.0	5.8	44.1
Soybean	10/26/17	5/7/18	In band	3121	4.78	0.44	3.88	147.8	13.4	118.9
Soybean			Between band	3160	3.41	0.31	2.92	108.2	9.8	92.5
Corn			-	2805	3.02	0.37	3.11	84.7	10.3	87.4
Soybean	11/2/18	5/2/19	-	1650	4.05	0.38	3.19	66.7	6.2	52.7
Corn		5/6/19	-	1186	5.71	0.48	3.62	67.7	5.7	43.0

Corn yields: 2016 - 2018

Table 8 gives the treatment effects on grain yield of corn in corn-soybean rotation for 2016 through 2018. In 2016, plots LFM150NT had a statistically greater corn yield than EFM150NT, which in turn had a significantly higher yield than EFM150NT+R. It should be noted that the fall of 2015 was wetter than average, as was June, so the early fall manure application may have had more of a corn yield issue in 2016 than in years with normal rainfall. The transition from spring UAN to LFM in the cover crop plots may also have contributed to the yield differences noted in 2016.

Table 8. Yield data for the 2016 through 2018 crop years for corn in corn-soybean rotation.

System	SU150	EFM150NT	EFM150NT+R	LFM150NT
	Rotated corn yield, bu ac^{-1}			
2016	228a	168c	142d	194b
2017	239a	158c	162c	221b
2018	242a	159d	175c	188b

Yields with the same letter within year are not significantly different at $P \leq 0.05$.

In 2017, LFM150 had a significantly higher (+64 bu ac^{-1}) yield than EFM150NT. The yield in EFM150NT+R was not statistically different than EFM150NT. In 2018, LFM150NT averaged 29 bu ac^{-1} higher yield than EFM150NT. The yield in 2018 for EFM150NT+R was significantly higher than EFM150NT. This was the first time that the cover crop treatment significantly out-yielded the no cover crop treatment on these plots. In all three years, the highest average corn yield was achieved with SU150.

Table 9 gives the yield results for continuous corn in 2016 through 2018. Averaged over 3 years, SM200 had a significantly higher corn yield (+38 bu ac^{-1}) compared to LFM200. Use of the nitrification inhibitor with LFM led a 12 bu ac^{-1} greater yield in 2017 and 21 bu ac^{-1} greater yield in 2018. There was no statistical difference in corn yield due to the 2.24 Mg ha^{-1} (1 ton ac^{-1}) gypsum applications compared to no gypsum.

Table 9. Continuous corn yield data for the 2016 through 2018 crop years.

System	LFM200+I	SM200	LFM200	LFM200+G
	Continuous corn yield, bu ac^{-1}			
2016	211*	224a	187b	179b
2017	222b	238a	210c	209c
2018	188b	215a	167bc	158c

* Treatment 3a was planted to soybean in 2015 so it was not included in the statistical analysis due to possible rotation effects. Yields with the same letter within year are not significantly different at the $P \leq 0.05$.

Corn yields: 2019

Corn yield comparisons among treatments in 2019 differ from other years due to delayed manure application in the fall of 2018. Manure was applied to the EFM plots on October 25th when soils were about 5.5°C (42°F), which we would consider a LFM application. Manure application to all LFM plots was delayed until the spring of 2019 due to late harvest, excessively wet soils, and frozen soil conditions in the fall of 2018. Tables 10 and 11 show 2019 yields for rotated corn and continuous corn, respectively.

Table 10. Yield data for the 2019 crop year for corn in corn-soybean rotation.

System	SU150	~~EFM~~ LFM150NT	~~EFM~~ LFM150NT+R	~~LFM~~ SM150NT
	Rotated corn yield, bu ac^{-1}			
2019	228a	210b	224a	228a

Yields with the same letter are not significantly different at $P \leq 0.05$.

Table 11. Continuous corn yield data for the 2019 crop year .

System	~~LFM~~ SM 200+I	SM200	~~LFM~~ SM 200	~~LFM~~ SM200+G
	Continuous corn yield, bu ac^{-1}			
2016	214a	212a	214a	213a

Yields with the same letter are not significantly different at $P \leq 0.05$.

In rotated corn, the cover crop treatment had a significantly higher yield (+14 bu ac^{-1}) compared to no cover crop. Delaying manure application from late fall to spring resulted in an 18 bu ac^{-1} yield advantage. It is notable that when manure was applied in the spring, there was no yield difference between the manure and spring UAN treatments, suggesting that the yield difference observed previously between fall manure and spring UAN is likely due to the timing effect, rather than the different N source. All continuous corn plots received manure in the spring of 2019. There were no significant yield differences between treatments and no yield effect from the Instinct treatment applied with spring manure. The minimal yield variability between treatments when all manure was spring applied suggests that the plots otherwise perform consistently and the yield differences noted in prior years with fall vs. spring manure are due to timing and not random variation.

Soybean yields: 2017 - 2019
Treatment effects on soybean yield in corn-soybean rotation for 2017 through 2019 are shown in Table 12. No manure was applied prior to soybeans in any of the treatments. Soybean yields in 2016 are not reported due to 2016 being a transition year to different nitrogen management practices. In 2017, the cover crop treatment had a slightly lower yield than the comparable no cover crop treatment. In 2018, SU150 had a significantly greater soybean yield relative to the other treatments. The trend reversed in 2019, with SU150 having a significantly lower yield than the other treatments. The causes of this variability in soybeans are unknown but could relate to plot-to-plot variation in growing conditions. There was no statistical difference in yields between treatments when looking at 3-yr average.

Table 12. Soybean yield data for the 2017 through 2019 crop years.

System	SU150	EFM150NT	EFM150NT+R	LFM150NT
	Soybean yield, bu ac^{-1}			
2017	66.9a	66.4a	63.6b	64.5b
2018	70.1a	65.9b	66.4b	67.1b
2019	63.6b	69.0a	67.0a	68.6a
3-yr avg.	66.9a	67.1a	65.7a	66.7a

Discussion

The pattern of N concentrations and losses was affected by the interaction of precipitation patterns with manure application timing in this study. Precipitation was substantially above average in 2016 and 2018, leading to greater than normal drainage in those years. Drainage depth (drainage volume converted to depth of water over the drainage area) across all treatments averaged 11.4 cm (4.5 in) from 2001 to 2015 (data not shown). Drainage depth averaged 35.3 cm (13.9 in) in 2016 and 41.1 cm (16.2 in) in 2018, thus increasing the likelihood that nitrate-N would leach through the profile before plant uptake could occur. In general, drainage depth does not appear to have a major influence on nitrate-N concentrations but is correlated to overall N loss on a mass basis. This can be seen in Table 5, where large losses occurred in 2016 and 2018, with relatively little N loss in 2019, which was a year with average rainfall.

It is important to note that fall swine manure was applied at inconsistent N rates among treatments and years (data not shown), which could add to the variation in nitrate-N concentrations and total N loss. Applying a consistent N rate with livestock manure is challenging due to variation between manure samples taken to estimate manure rates vs. samples taken during application to determine the actual rate applied. This factor adds uncertainty when making inferences about treatment effects. Previous research on these plots indicates that the target volume of manure was achieved with ± 5% accuracy. However, manure N in the pre-sample used to estimate manure volume needed was 10 – 30% higher than actual N in the sample taken during application from samples taken over an 8-yr period. Since actual N content is unknown during application, manure rates must be estimated based on expected variation in N content between pre-sample and day-of-application samples. This can result in N rates that miss the target rate by ± 20%.

Comparing flow-weighted annual nitrate-N concentrations and losses between the EFM150NT and EFM150NT+R treatments shows that the cover crop was effective in reducing nitrate-N loss through the drainage system. Cover crops have been shown to immobilize N and reduce mineral N levels in soil (Thilakarathna et al., 2015), leading to less nitrate-N leaching during the periods of high subsurface flow (Salmerón et al., 2010). This can be particularly effective for reducing nitrate-N leaching during periods of no N uptake by the cash crop and is the likely mechanism behind reduced nitrate-N concentrations observed in this study. Nitrogen uptake in aboveground cereal rye biomass was substantial prior to both corn and soybeans, suggesting that significant recycling of both residual soil nitrate-N and manure N occurred.

Cereal rye cover crops have proven to be an effective tool for reducing nitrate-N losses via subsurface drainage systems in the Midwestern Corn Belt, but yield effects need to be taken into consideration when using a cover crop. Singer et al. (2008) found no significant impact on corn yield when a cereal rye and oat cover crop was used in conjunction with fall manure injection. The authors concluded that cover crops could increase nutrient capture with no adverse yield effects. However, our research site has a history of significant yield reductions with the rye cover crop in a system when all nitrogen was side-dressed as UAN after planting. This yield drag continued in 2016 as the system transitioned from spring UAN to early fall manure, with both corn and soybeans having significant yield reductions in the cover crop treatment. However, in 2017 this yield drag in corn disappeared, and in 2018 and 2019 the cover crop treatment significantly out-yielded the no cover crop treatment in an early fall manure system. Nitrogen release from the terminated cover crop was not measured in this study, but the results suggest that potential N tie-up by the cover crop had no adverse effect on yields beyond the 2016 transition year. Overall, the cover crop significantly improved water quality and did not affect 4-yr average yields in this study even with the yield loss from the transition year included in the average. This suggests that an early fall manure system is a good candidate for inclusion of a cover crop in the rotation.

The Instinct® nitrification inhibitor showed promise for improving yields when applied with fall manure, but there was no yield benefit when the inhibitor was included with a spring manure application in 2019. The inhibitor had no detectable effect on water quality in this study. Similarly, the application of 2.24 Mg ha^{-1} (1 ton ac^{-1}) of gypsum in the fall of 2015 and 2017 had no observable effects on water quality or yields in this study.

Significant corn yield increases were observed in this study by delaying manure application from both early fall to late fall and from late fall to spring. The data from this study indicates that delaying fall manure applications until soils have cooled to below 50°F can help to protect water quality and enhance yields. While application in the spring presents logistical challenges and potential for compaction if soils are wet, yield data suggests that the economic benefit might justify moving to a spring pre-plant or side-dress manure application system where feasible. The economics of fall vs. spring manure application is a research question that should be further explored in other research trials. Coupling a continuous corn system with a cover crop under different manure application timing scenarios is another area that warrants research.

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