Agricultural Water Management 211 (2019) 81–88

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Impacts of nitrogen application timing and cover crop inclusion on subsurface drainage water quality

Michael D. Ruffatti[a], Richard T. Roth[b], Corey G. Lacey[b], Shalamar D. Armstrong[b,*]

[a] Department of Agriculture, Illinois State University, 301 North Main Street, Normal, IL 61790-5020, USA
[b] Department of Agronomy, Purdue University, 915 West State Street, West Lafayette, IN 47907-2053, USA

ARTICLE INFO

Keywords:
In-field conservation practices
Nutrient loss reductions
Cereal rye
Daikon radish
Nitrate leaching
Unfertilized control

ABSTRACT

Significant reductions in nitrogen loading from sub-surface drainage fields of the Upper Mississippi River Basin to the Gulf of Mexico will most likely be achieved from the mass adoption of nutrient loss reduction strategies at a watershed scale. Few studies have quantified the efficacy of cover crops to reduce NO_3-N loading in nitrogen fertilizer management systems, where the dominant portion of the N rate is applied in the spring or fall, both of which are common practices in the Upper Mississippi River Basin. In this experiment we quantified the impact of N application timing and cover crop inclusion on NO_3-N loss (leaching) from agricultural sub-surface drainage within five nitrogen management scenarios: a zero control, applying the dominant portion of the N rate in the spring, applying the dominant portion of the N rate in the fall, augmenting the a spring and Fall N application system with cover crop. Each of the five nitrogen management scenarios was replicated three times on individually monitored sub-surface drainage plots established in Lexington, IL. During the experiment, a cereal rye (*Secale cereal* L.) and radish (*Raphanus sativus* L.) blend was interseeded within both corn (*Zea mays* L.) and soybean (Glycine max L.). Fertilizer N application timing did not affect cover crop growth or N uptake. The inclusion of cover crop resulted in more consistent and greater NO_3-N loss reductions relative to adjusting fertilizer N application timing from fall to spring. Cover crop reduced the flow-weighted NO_3-N concentrations by 39% and 38% and the N load by 40% and 47% when added to spring and fall fertilizer N management systems, respectively. Cover crop proved to be effective in reducing NO_3-N loss through sub-surface drainage across the spectrum of N fertilizer management systems common to the Upper Mississippi River Basin.

1. Introduction

Inorganic fertilizer nitrogen (N) management for row crop production only affects a minute percentage of the soils total N; however, within exported tile drainage-water inorganic N is a significant proportion of the total N (Blesh and Drinkwater, 2014). Furthermore, low fertilizer N efficiency of row crops combined with high tile drainage density in the Upper Mississippi River Basin (UMRB) contribute to the export of excessive N, local water quality issues and the hypoxic zone in the Gulf of Mexico (Gardner and Drinkwater, 2009; Smil, 1999). The severity of this N loading issue resulted in the United States Environmental Protection Agency Gulf of Mexico Hypoxia Task Force requiring UMRB states to develop a Nutrient Loss Reduction Strategy (NLRS) to reduce N and P loading (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). The NLRS Science Assessment of each UMRB state estimated that the manipulation of N application timing and rate result in an N loading reduction of 10–20% on tile-drained land, while cover cropping alone was estimated to reduce N loading by 28–40% (David et al., 2013; Illinois Nutrient Loss Reduction Strategy, 2015; Iowa Nutrient Reduction Strategy, 2013; Minnesota Nutrient Reduction Strategy, 2014; Missouri Nutrient Loss Reduction Strategy, 2014; Wisconsin Nutrient Reduction Strategy, 2013). Among all UMRB NLRS, cover crops demonstrated the highest efficacy to achieve the proposed non-point source nutrient loss reduction targets on a watershed scale.

The scientific literature has demonstrated that actively growing cover crops (CC) influence the concentration of nitrate (NO_3-N) in tile water during the fallow period of the year, which frequently results in less nitrate loading (Drury et al., 2014; Kaspar et al., 2007, 2012; Strock et al., 2004). CC absorb inorganic N from the residual, fertilized and mineralized soil N pools affecting the distribution of inorganic N in the soil profile (Kaspar et al., 2007; Lacey and Armstrong, 2014). The presence of both winter-kill and winter hardy CC species result in significantly less soil inorganic N at lower soil depths closer to the location

* Corresponding author.
E-mail address: sarmstro@purdue.edu (S.D. Armstrong).

https://doi.org/10.1016/j.agwat.2018.09.016
Received 24 January 2018; Received in revised form 31 August 2018; Accepted 6 September 2018
Available online 02 October 2018

of the tile drainage (Cooper et al., 2017; Lacey and Armstrong, 2014). Studies have also demonstrated that evapotranspiration from CC reduces the soil moisture content in the fallow period without negatively affecting cash crop yield (Basche et al., 2016). This reduction in soil moisture content has resulted in a higher soil matric potential, a lower soil leaching potential, and less tile drainage resulting in reduced N loading (Daigh et al., 2014; Kaspar et al., 2007; Qi and Helmers, 2010).

Few studies have quantified the environmental impacts of systematic conservation, where multiple nutrient loss reduction strategies are concurrently applied to one field, such as N application timing and CC. In spring N application systems, the ability of cover crops to improve water quality has been documented in the literature. For example, in Iowa, Kaspar et al. (2007) studied the system of spring N management combined with CC inclusion and determined that a rye CC significantly reduced the average annual flow-weighted NO_3-N concentration of drainage water by 50% or more compared to the control. In Minnesota, Strock et al. (2004) also studied the impact of establishing a cereal rye CC following corn, within a spring N application system, and found a 13% reduction in NO_3-N loading via tile drainage. While fertilizer N applications have been trending toward the spring, there remains a large percentage (41–46%) of row crop acreage in the UMRB that receives fall-applied N (Bierman et al., 2012; Illinois Nutrient Loss Survey Results, 2016; Lemke et al., 2011; Ribaudo et al., 2012; Smiciklas et al., 2008). The source of N during this fall N application could be anhydrous ammonia, ammonium phosphate or livestock manure. Equipment and labor availability in the fall, reduced N fertilizer costs, and spring soil conditions have all been suggested as reasons for fall N application (Ribaudo et al., 2012; Smiciklas et al., 2008). To achieve the targeted surface area reduction of the Gulf of Mexico Hypoxic Zone established by the USEPA, all agricultural fertilizer N management systems common to the UMRB must significantly improve N retention. Currently, there remains a dearth of research concerning the ability of cover crops to reduce tile nitrogen concentrations within fall N application systems, and that investigates the concurrent adoption of both N timing and CC. Therefore, the objectives of this study were to quantify the impact of N application timing and CC inclusion on the flow-weighted NO_3-N concentration and loading from agricultural tile drainage within five N management scenarios (i) applying the dominant portion of the N rate in the spring, (ii) applying the dominant portion of the N rate in the fall, (iii) augmenting the a spring N system with CC, (iv) and augementing the Fall N application system with CC, and (v) a zero control without N fertilizer or CC.

2. Materials and methods

2.1. Site description and cultural practices

The experimental site was located east of Lexington, Illinois (40°38′25.9″N 88°43′11.2″W) at the Illinois State University Nitrogen Management Research Field Station. The predominant soil types within the approximately 10 ha site are Drummer and El Paso (67.5%) and Hartsburg (26%) silty clay loams, both soil types are common in the central Illinois region and are classified as poorly drained with a 0–2% slope. The drainage system was established on April 18, 2014. Three 7.6 cm inside diameter tile laterals spaced 13.7 m apart were installed in each plot at an approximate depth of 0.9 m. The laterals merge 4.5 m from a controlled drainage structure before connecting to 15.2 cm main tile. Precipitation and air temperature data were collected from a weather station located at the experimental site in each year of the experiment.

The production history of this field consists of an eight-year rotation of rain-fed strip-tilled corn (*Zea mays* L.) and no-till soybeans (*Glycine max* L.), which were both harvested for grain. This experiment was a continuation of these cultural practices. The site was comprised of fifteen individually tile-drained 0.65 ha plots, each of which included a tile-water monitoring station. The experiment consisted of five

Table 1
Nitrogen Fertilizer source and nitrogen rate applied during the 2014–2015 and 2016–2017 corn years.

Nitrogen Source	Fall Nitrogen System		Spring Nitrogen System	
	2014–2015 kg N ha^{-1}	2016–2017	2014–2015	2016–2017
Fall Diammonium Phosphate	40	50	40	50
Fall Anhydrous Ammonia	112	134	0	29
Spring Anhydrous Ammonia	72	90	184	195
Total	224	274	224	274

treatments replicated three times arranged in a complete randomized block design. The experimental treatments included a zero control (no N, no CC), a spring dominated nitrogen management system with and without CC, and a fall dominated nitrogen management system with and without CC (Table 1). All fall anhydrous ammonia (AA) was applied with a nitrification inhibitor, and application occurred only once soil temperatures fell below 10 °C. The remaining N was applied as a side-dress AA application, without an inhibitor, near the V6 growth stage. Specific N sources and rates for each treatment can be found in Table 1.

Corn and soybeans were planted in 76.2 cm rows using a John Deere 1770 N T 24-row planter. Corn was planted at a targeted rate of 86,485 seeds ha^{-1} on April 30, 2015, and April 25, 2017. Population counts resulted in average corn plant stands of 83,520 plants ha^{-1} in 2015 and 87,990 plants ha^{-1} in 2017. Soybeans were planted at a rate of 308,875 seeds per hectare on May 7, 2016. Weather conditions in the early spring of the 2016 growing season caused poor emergence and resulted in an average population of approximately 214,977 soybean plants per hectare. Due to this reduction in the plant stand, a replant at a rate of 135,905 seeds per hectare occurred on May 25, 2016. After a population check, the replant stand was found to be at approximately 133,434 plants per hectare, which resulted in an average of 348,411 plants per ha. Harvest was conducted on September 23, 2015, October 21, 2016, and October 9, 2017, using a John Deere S670 combine with a John Deere 608C 8 row head for corn, and a John Deere 635FD 10.7-meter flex draper head for soybeans (Deere & Company, Moline, Illinois, U.S.).

The CC mixture for this study was a 92% cereal rye (*Secale cereal* L.) and 8% daikon radish (*Raphanus sativus* L.) blend calculated by weight, first established in September 2014 and was grown in the same plots each year. The CC were inter-seeded at a rate of 84 kg ha^{-1} into the standing crops using a Hagie STS12 (Hagie Manufacturing Company, Clarion, Iowa, U.S.) modified with an air seeding box in early September. Throughout the study, the daikon radish self-terminated through vegetative desiccation in mid-to-late December following several days of subfreezing weather conditions. The cereal rye, however, is a winter hardy species that was chemically terminated at least two weeks before the anticipated planting of the cash crop. Along with the chemical termination of the CC, the research plots received pesticide applications dependent upon the primary crop and weather conditions.

2.2. Cover crop shoot samples

CC sampling occurred in both the fall and spring to document both above ground shoot biomass and nitrogen uptake. Within each treatment, two 1 m^2 quadrants were randomly chosen, and the CC shoot biomass was collected to create a representative sample for each treatment. This sampling technique is a modified version of Dean and Weil's method developed in 2009 (Dean and Weil, 2009). In fall 2015 and fall 2016 radish and rye shoot biomass was separated and analyzed by species. The CC biomass samples were oven dried at 60 °C and ground to pass through a 1-mm sieve. The dry weight of each biomass sample was determined and used to calculate both total CC biomass, as well as total CC nitrogen uptake. The dried and ground CC shoot biomass were analyzed for percent total nitrogen using a 0.1000 g sample via the use of a FLASH 2000 series dry combustion instrument (ThermoFisher Scientific, Waltham, Massachusetts, U.S.). The percent total nitrogen was then multiplied by total CC biomass to determine total CC nitrogen uptake (kg ha^{-1}).

2.3. Corn and soybean yield

Grain yields were calculated by harvesting the entire plot area. Grain weights were collected from a weigh wagon at harvest. A grain subsample was then collected, wieghed and dried to measure grain moisture content. Reported yields were corrected to 0.155 and 0.130 g g^{-1} moisture content for corn and soybean, respectively.

2.4. Water sampling

An automated tile water monitoring and sampling system was employed to determine the NO_3-N flow-weighted concentration and loading through the subsurface drainage system. The system included an ISCO 6712 automated water sampling unit, an ISCO 2105 communication module, and an ISCO 2150 data logger module (Teledyne Isco, Lincoln, Nebraska, U.S.), all of which were powered by a marine grade 12-volt battery maintained through the use of a solar panel and power inverter. The automated sampler collected a 200 ml sample every hour and formed a three-hour composite (600 ml) sample in each of the twenty-four bottles. At the completion of the sampling program, each plots hydrograph was analyzed and sampled to represent the base flow, rising limb, peak flow, falling limb, and the inflection point of the hydrograph using the Flowlink software (Teledyne Isco, Lincoln, Nebraska, U.S.). Each of the samples selected to be analyzed was filtered with 0.45-micron filter paper to remove any suspended particulates and analyzed for NO_3-N concentrations using a Lachat QuikChem® 8500 series flow injection analysis autosampler (Hach Company, Loveland, Colorado, U.S.).

2.5. Statistical analysis

The experimental design was a complete random block with three replications of five treatments. For each plot, the variables of average flow-weighted NO_3-N concentration, cumulative NO_3-N load, cover crop aboveground biomass, cover crop N uptake, and corn and soybean yield were calculated individually by year. Data for all three years were combined and the main effects of block, year, cover crop, and N application timing were analyzed, along with the interactions of cover crop by N application timing, cover crop by year, N application timing by year, and cover crop by N application timing and year using the PROC MIXED procedure (SAS 9.4, 2017). For all analyses, the LSMEANS statement was used to apply the Tukey's test at the 0.05 probability level to compare treatment means when the analysis of variance indicated significant effects at the 0.05 alpha level.

3. Results

3.1. Weather data

The 2014 hydrologic year (the hydrologic year was determined based on the average planting date of the cover crop, September-August) was the coldest relative to 2015 and 2016, averaging 1.3 °C cooler than the 30-year average. There was relatively little variation in air temperature between the 2015 and 2016 hydrologic years, averaging 1.2 and 1.1 °C above the 30-year average, respectively (Table 2).

To examine the influence of weather on different phases of the cropping system, each hydrologic year was divided into cover crop (September–April) and cash crop (May–August) growing seasons (Fig. 1). Additionally, when examining the cover crop growing season, both the fall and spring portions were considered separately. The average ambient air temperatures for the fall portion (September–December) of the 2014 cover crop growing was slightly below the regional norm, while the fall of 2015 and 2016 were slightly above the 30-year average. Specifically, average air temperatures in November of 2015 and 2016 were on average 6.6 °C warmer than in 2014. In the spring portion (January–April) of the cover crop growing seasons, an average deviation from the 30-year norm of −2.1, +1.2, and + 2.9 °C was observed in 2014, 2015, and 2016, respectively. In the spring of 2017, January and February air temperatures were warmer than in spring 2015 and 2016. For example, the temperatures were 3.6 and 12.2 °C warmer in January and February of 2017 compared to the same months in 2015. Average monthly temperatures during the cash crop growing season were similar to the 30-year norm and did not indicate any limitation to corn or soybean growth.

Annual precipitation in 2014, 2015, and 2016 hydrologic years was 163.3 mm and 86.1 mm above the 30-year average and 221.0 mm below average, respectively (Table 2). The fall cover crop growing seasons had +137.5, +58.2, and −99.3 mm of precipitation, relative to the 30-year average, in 2014, 2015, and 2016 respectively. Spring cumulative precipitation deviated from the 30-year average by –127.1, −86.7, and −32.1 mm in 2015, 2016, and 2017, respectively. Despite having below average annual rainfall, the 2016 hydrologic year had the greatest spring precipitation of all three years. Specifically, 180.6 mm of cumulative rainfall in March and April of 2017, which was above the 30-year norm and had 98 and 38.8 mm greater precipitation relative to the springs of 2015 and 2016, respectively.

Cumulative precipitation during the cash crop growing seasons of 2014, 2015, and 2016 hydrologic years was +152.9, +114.6, and −89.7 mm compared to the 30-year average, respectively. In 2014 hydrologic year, which was the wettest of the three years; May, June and July cumulative precipitation were 29.2 and 92.8 mm greater relative to the same period in 2016 or 2017, respectively. Specifically, June of 2015 had the highest precipitation on record for the state of Illinois.

3.2. Cover crop biomass and N uptake

The main effect of N application timing did not significantly affect cover crop biomass or N uptake. For this reason, results and discussion regarding cover crop growth will use averages across N application timing unless otherwise stated.

3.2.1. 2014–2015 cover crop growing season

During the fall of 2014, the rye/radish mixture accumulated a total biomass of 298.7 kg ha^{-1} and a total N uptake of 11.7 kg ha^{-1}. By the following spring, rye accumulated significantly greater biomass (1106.7 kg ha^{-1}), and N uptake (53.6 kg N ha^{-1}) compared to fall of 2014 (Tables 3 and 4). The 2014–2015 cover crop growing season was coldest observed (Fig. 1) during the study, which potentially limited fall rye and radish growth. Cold conditions combined with below average spring precipitation likely limited spring rye growth as well.

3.2.2. 2015–2016 cover crop growing season

The 2015 cover crop season preceded a soybean cash crop, and no N fertilizer was applied. In contrast to the other CC seasons, the CC mixture only had the potential to interact with naturally mineralized N and residual N within the soil from the previous corn season. In the fall of 2015, the CC mixture accumulated a total biomass of 1417.3 kg ha^{-1} and absorbed 59.4 kg N ha^{-1}. Above average fall temperatures and precipitation provided an opportunity to accumulate CC growth. As a result, significantly greater fall biomass and N uptake occurred relative to the fall of 2014 and 2016. Specifically, above average air temperatures in November 2015 contributed to increased CC growth and a late-November radish termination date.

Table 2
Average ambient air temperature and annual precipitation for 2014, 2015, 2016 hydrologic years.

	Temperature, °C				Precipitation, mm			
	2014	2015	2016	30-yr Avg	2014	2015	2016	30-yr Avg
September	17.7	20.3	20.5	18.8	98.8	69.1	78.5	83.4
October	11.3	12.2	14.6	12.0	104.1	45.7	42.9	86.1
November	0.6	7	7.3	4.9	41.9	100.1	66	78.2
December	−0.1	4.2	−2.4	−1.8	201	151.6	21.6	60.6
January	−4.6	−3.6	−1	−3.8	39.9	15.7	37.6	57.5
February	−8.3	−0.4	3.9	−2.1	13.7	19.1	13	51.8
March	2.5	7.7	4.7	4.3	22.4	74.7	85.1	63.3
April	11.4	10.5	13.1	10.9	60.2	67.1	95.5	90.7
May	18	16.6	16	17.1	131.6	102.9	73.9	108.1
June	21.5	23.2	22.6	22.2	179.1	102.4	95	100.5
July	22.3	23.2	23.15	23.9	139.2	157	32.8	98.3
August	21.2	23.2	19.83	22.9	104.1	153.4	109.8	94.2
Total Average	9.5	12.0	11.9	10.8	1136.0	1058.8	751.7	972.7
Deviation from 30-yr Avg	−1.3	1.2	1.1		163.3	86.1	−221.0	

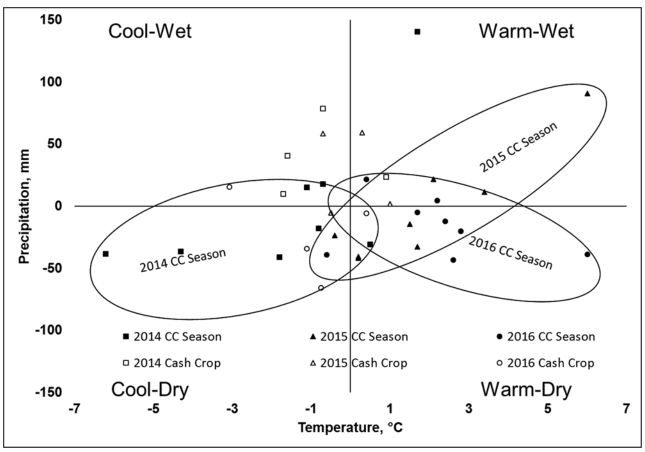

Fig. 1. Deviation from the 30-year regional average precipitation versus deviation from the 30-year regional average temperature for the 2014, 2015, and 2016 hydrologic years separated by cover crop and cash crop season.

By chemical termination in the spring of 2016, rye accumulated 1223.3 kg ha^{-1} of shoot biomass and 31.4 kg N ha^{-1} of N uptake; which was on average less than the total growth that occurred in the preceding fall. However, spring rye resulted in significantly greater biomass (+ 587.4 kg ha^{-1}) and greater N uptake (+ 6.3 kg N ha^{-1}) relative to the rye alone growth observed in the previous fall.

3.2.3. 2016–2017 cover crop growing season

In the fall of 2016, the CC mixture accumulated an average total biomass of 617.7 kg ha^{-1} and absorbed 22.9 kg N ha^{-1}. This fall was the driest of the study with precipitation 99.3 mm below the 30-year average. It is likely, that dry conditions limited both rye and radish fall growth. In contrast to the fall of 2015, in which radish accounted for the largest percentage of fall growth; fall 2016 radish growth resulted in only 135.7 kg ha^{-1} of shoot biomass and 5.3 kg N ha^{-1} of N Uptake.

Table 4
Cover crop nitrogen uptake for each species at both the fall and spring sampling dates for the 2014–2015, 2015–2016, and 2016–2017 years.

Cover Crop		Sampling Period					
		2014–2015		2015–2016		2016–2017	
		Fall[‡]	Spring	Fall	Spring	Fall	Spring
Treatment	Species	kg N ha^{-1}					
FCC[†]	Radish			32.2[a]		5.1[a]	
	Cereal Rye	12.3[Aa§]	61.5[Ba]	22.7[Aa]	29.1[Aa]	15.9[Aa]	91.5[Ba]
SCC	Radish			36.4[a]		5.5[a]	
	Cereal Rye	11.0[Aa]	45.6[Ba]	27.5[Aa]	33.7[Aa]	19.2[Aa]	70.3[Bb]

[†] FCC = fall applied nitrogen with cover crops, SCC = spring applied nitrogen with cover crops.
[‡] Species were not separated in the fall of 2014 and thus, the value represented in the fall 2014 column is representative of both cereal rye and daikon radish biomass accumulation.
[§] Different capital letters indicate significant differences within treatment and year among sampling periods at an alpha level of 0.05. Different lower case letters within the same sampling period and cover crop species indicate significant differences among treatments at an alpha level of 0.05.

Table 3
Cover crop shoot biomass for each species at both the fall and spring sampling dates for the 2014–2015, 2015–2016, and 2016–2017 years.

		Sampling Period					
		2014–2015		2015–2016		2016–2017	
Treatment	Cover Crop Species	Fall[b] kg ha^{-1}	Spring	Fall	Spring	Fall	Spring
FCC[a]	Radish			755.9		126.5	
	Cereal Rye	332.2[Ac]	1179.6[B]	619.5[A]	1072.7[B]	422.7[A]	2283.5[B]
SCC	Radish			806.9		144.8	
	Cereal Rye	265.2[A]	1033.7[B]	652.2[A]	1373.8[B]	541.3[A]	2110.5[B]

[a] FCC = fall applied nitrogen with cover crops, SCC = spring applied nitrogen with cover crops.
[b] Species were not separated in the fall of 2014, thus the value represented in the fall 2014 column is representative of both cereal rye and daikon radish biomass accumulation.
[c] Different capital letters indicate significant differences within species between the fall and spring sampling dates for a given year at an alpha level of 0.05.

Table 5
Grain yields for the 2015, 2016, and 2017 cash crop growing seasons.

Treatment[a]	2015 Corn Mg ha^{-1}	2016 Soybeans	2017 Corn
FN	12.76^{AB}[b]	3.96^{A}	13.77^{A}
FCC	12.74^{AB}	3.77^{A}	10.69^{B}
SN	13.19^{A}	4.07^{A}	13.91^{A}
SCC	12.28^{B}	3.90^{A}	11.41^{B}
ZC	4.59^{C}	3.97^{A}	5.32^{C}

[a] FN = Fall Nitrogen, FCC = Fall Nitrogen with Cover Crop, SN = Spring Nitrogen, SCC = Spring Nitrogen with Cover Crop, ZC = Zero Control.
[b] Different capital letters within a column denote significant differences between treatments within year at an alpha level of 0.05.

Rye, however, accounted for 78% (482.0 kg ha^{-1}) and 77% (17.6 kg N ha^{-1}) of the total fall shoot biomass and N uptake, respectively. Above average temperatures in February and March 2017 allowed the rye to begin growth earlier, relative to the first two springs. This combined with greater precipitation, relative to spring 2015 or 2016, resulted in ideal rye growing conditions. As a result, the greatest rye biomass (2197 kg ha^{-1}) and N uptake (80.9 kg N ha^{-1}) was observed in the spring of 2017.

3.3. Corn and soybean yields

In 2015, the inclusion of CC significantly reduced corn grain yields by 7% within the spring dominated nitrogen application system. However, CC did not significantly affect corn grain yields in the fall dominated nitrogen application system. Furthermore, nitrogen application timing had no significant effect on corn grain yields (Table 5). During the 2016 soybean year, no significant differences were observed in grain yield between any of the experimental treatments. The presence of CC resulted in significant decreases in corn grain yield in both the fall (22%) and spring (16%) dominated nitrogen application systems in 2017. However, like the previous corn season, no significant differences were observed as a result of N application timing (Table 5).

3.4. Nitrogen application timing and cover crop inclusion on water quality

3.4.1. Impact of nitrogen application timing on tile Nitrate-N loss

In the 2014 hydrologic year, tile water flow-weighted NO_3-N concentration was significantly greater in the fall dominated nitrogen treatment relative to the spring dominated nitrogen treatment by 18% (Table 6); though this did not translate to significantly different NO_3-N loads between the two application timings (Table 7). However, in the 2015 or 2016 hydrologic years, nitrogen application timing did not have a significant impact on annual average flow-weighted NO_3-N concentrations. Likewise, there was not a significant impact on annual

Table 6
Average annual flow-weighted NO_3-N concentrations for each treatment for the 2014–2016 hydrologic years.

Treatment[a]	2014 Hydrologic Year mg L^{-1}	2015 Hydrologic Year	2016 Hydrologic Year
FN	10.48^{B}[b]	5.44^{AB}	13.98^{A}
FCC	9.52^{AB}	3.53^{A}	5.48^{B}
SN	8.88^{AC}	5.97^{A}	11.80^{A}
SCC	7.93^{AC}	3.64^{B}	4.65^{B}
ZC	7.18^{C}	4.29^{AB}	8.92^{C}

[a] FN = Fall Nitrogen, FCC = Fall Nitrogen with Cover Crop, SN = Spring Nitrogen, SCC = Spring Nitrogen with Cover Crop, ZC = Zero Control.
[b] Different capital letters within a column indicate significant differences between experimental treatments for that given hydrologic year at an alpha level of 0.05.

Table 7
Average annual total NO_3-N load for each treatment for the 2014–2016 hydrologic years.

Treatment[a]	2014 Hydrologic Year kg ha^{-1}	2015 Hydrologic Year	2016 Hydrologic Year
FN	42.45^{A}[b]	38.46^{AB}	36.18^{A}
FCC	37.51^{A}	19.35^{A}	13.81^{B}
SN	40.73^{A}	63.83^{B}	42.32^{A}
SCC	36.04^{A}	25.85^{A}	15.12^{B}
ZC	44.71^{A}	58.29^{AB}	42.32^{AB}

[a] FN = Fall Nitrogen, FCC = Fall Nitrogen with Cover Crop, SN = Spring Nitrogen, SCC = Spring Nitrogen with Cover Crop, ZC = Zero Control.
[b] Different capital letters within a column indicate significant differences between experimental treatments for that given hydrologic year at an alpha level of 0.05.

tile N loads during any year of the study.

Soybeans were grown during the 2015 hydrologic year as part of the on-going corn-soybean crop rotation common to the region; therefore, no N fertilizer was applied. Though no N fertilizer was applied, there were slightly greater concentrations in the spring dominated nitrogen treatment relative to the fall dominated nitrogen treatment; which agrees with the 1.65 times greater NO_3-N load in the spring dominated nitrogen treatment compared to the fall dominated nitrogen treatment. These findings are similar to those of Pittelkow et al. (2017) who reported on average greater NO_3-N concentration and load in the soybean phase of a corn-soybean rotation when N was applied in the spring relative to the fall.

During the 2016 hydrologic year, the fall dominated nitrogen treatment resulted in 18% greater NO_3-N flow-weighted concentration relative to the spring dominated nitrogen treatment; however, NO_3-N loads were 14% lower in the fall dominated nitrogen treatment compared to the spring dominated nitrogen treatment. Though not significant, three-year average annual NO_3-N concentrations were 11% less in the spring dominated nitrogen treatment compared to the fall dominated nitrogen treatment; but NO_3-N loads were 25% greater in the spring dominated nitrogen treatment (48.9 kg N ha^{-1}) relative to the fall dominated nitrogen treatment (39.0 kg N ha^{-1}) (Tables 6 and 7).

3.4.2. Impact of cover crops on tile Nitrate-N loss

Cover crops did not significantly affect flow-weighted NO_3-N concentration or load during the 2014 hydrologic year within N application timing. Averaged across N timing, CC inclusion resulted in 10% less flow-weighted NO_3-N concentration and 11% less NO_3-N load. The spring dominated nitrogen with cover crop treatment significantly reduced the NO_3-N concentration by 24% compared to the fall dominated nitrogen treatment and resulted in an N load reduction of 34% (Tables 6 and 7, and Fig. 2a). There were no significant differences in flow-weighted concentration or N load for the fall dominated nitrogen with cover crop treatment relative to the spring dominated nitrogen treatment.

During the 2015 hydrologic year, cover cropping significantly reduced NO_3-N concentration by 39% and NO_3-N load by 59% in the spring dominated nitrogen with cover crop treatment relative to the spring dominated nitrogen treatment. Furthermore, there was a trend for cover crops to reduce flow-weighted NO_3-N concentration ($P = 0.119$) 35% and NO3-N load ($P = 0.187$) by 50% in the fall dominated nitrogen with cover crop treatment compared to the fall dominated nitrogen treatment. No significant difference between the spring dominated nitrogen with cover crop and fall dominated nitrogen treatments were observed. However, the flow-weighted NO_3-N and N loads were significantly less in the fall dominated nitrogen with cover crop treatment relative to spring dominated nitrogen treatment by 40%

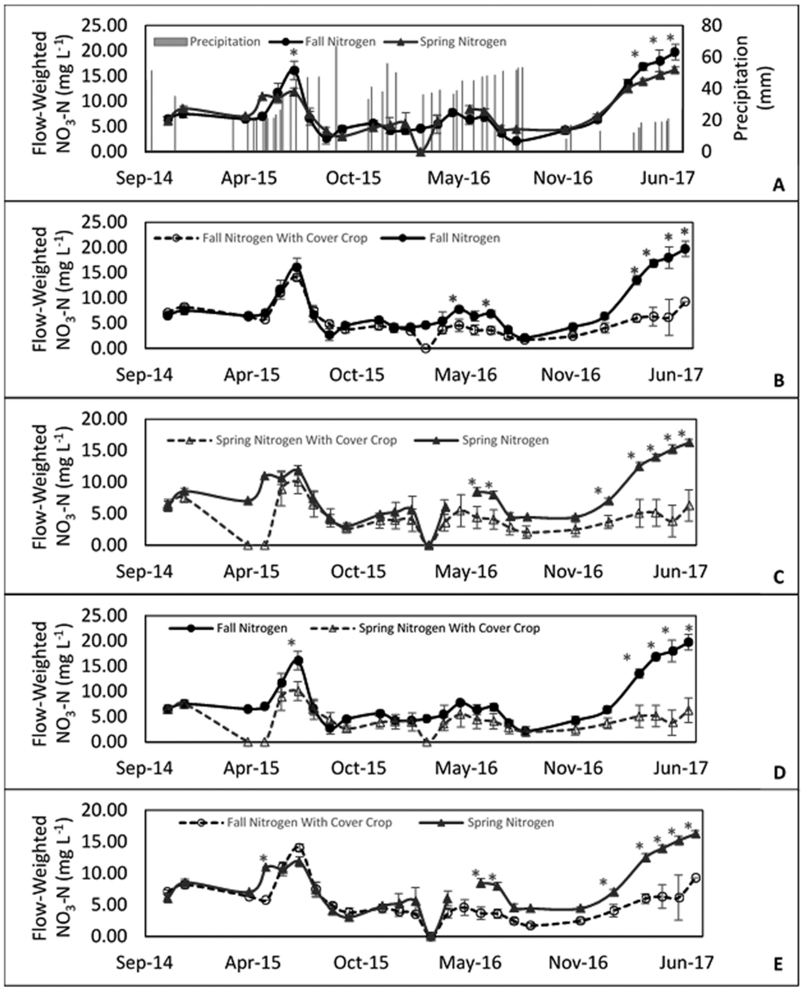

Fig. 2. Monthly average flow-weighted NO_3-N concentrations and precipitation by rain fall event. for September 2014 through June 2017. Significant differences at an alpha level of 0.05 between treatments within a given month are denoted with an asterisk (*). FN = Fall Nitrogen, FCC = Fall Nitrogen with Cover Crop, SN = Spring Nitrogen, SCC = Spring Nitrogen with Cover Crop.

and 70%, respectively.

In the 2016 hydrologic year, both cover crop treatments resulted in a significant reduction of 61% in flow-weighted NO_3-N concentration when compared to their respective non-cover cropped treatments. CC inclusion resulted in significant NO_3-N load reductions of 62% within the fall N system and 64% for the spring N system. The spring dominated nitrogen with cover crop treatment significantly reduced both NO_3-N concentration and N load compared to the fall dominated nitrogen treatment by 67% and 58%, respectively. Additionally, both NO_3-N concentration and load were 54% and 67% less in the fall dominated nitrogen with cover crop treatment relative to the spring dominated nitrogen treatment.

3.4.3. Tile Nitrate-N loss from the zero control treatment

Within the 2014 hydrologic year, the tile flow-weighted NO_3-N concentration (7.18 mg L^{-1}) of the zero control was significantly less relative to the fall dominated nitrogen (10.48 mg L^{-1}) and fall dominated nitrogen with cover crop (9.52 mg L^{-1}) treatments and was similar to both the spring dominated nitrogen and spring dominated nitrogen with cover crop treatments (Table 6). The zero control flow-weighted NO_3-N concentration (4.29 mg L^{-1}) was similar to all treatments in the 2015 hydrologic year. During the 2016 hydrologic year, flow-weighted NO_3-N concentrations in the fall dominated nitrogen with cover crop (5.48 mg L^{-1}) and spring dominated nitrogen with cover crop (4.65 mg L^{-1}) treatments were significantly lower relative to the zero control (8.29 mg L^{-1}). On the other hand, the fall dominated nitrogen (13.98 mg L^{-1}) and spring dominated nitrogen (11.80 mg L^{-1}) treatments resulted in significantly greater flow-weighted NO_3-N concentrations when compared to the zero control (8.92 mg L^{-1}). When considering NO_3-N load, there was no significant difference between the zero control and all other treatments that received fertilizer N over the course of the experiment. However, on average the NO_3-N loading for treatments augmented with CC was 66% lower than the zero control (Table 7).

4. Discussion

4.1. Cover crop biomass growth and N uptake

Cover crops have been identified within the NLRS of UMRB states as the most efficient in-field practice to mitigate non-point source NO_3-N contributions to surface waterways. The efficacy of cover crops to generate NO_3-N reduction depends primarily on cover crop growth. In the current study, we observed considerable year to year variation in radish shoot biomass (120–894.6 kg ha^{-1}) and N uptake (5.7–40.6 kg N ha^{-1}); however, fall rye shoot biomass (465.2–683.3 kg ha^{-1}) and N uptake (17.2–26.1 kg N ha^{-1}) was relatively consistent. These observations suggest that radish influenced the variation in fall growth of the cover crop mixture. The data also demonstrated that the selection of a cover crop mixture allows for responsive cover crop growth in the event of abnormal increases in air temperature and precipitation in the fall that create ideal conditions for N losses via leaching through tile drainage. Spring rye biomass (1098.7–2208.3 kg ha^{-1}) and N uptake (50.6–83.3 kg N ha^{-1}) were similar to what has been reported in the literature for rye grown as a monoculture (Johnson et al., 1998; Dean and Weil, 2009; Kaspar et al., 2012; Lacey and Armstrong, 2015). White and Weil (2010) also examined a rye/radish mixture over a two-year study. They reported rye, radish, and combined biomass ranges 763–869 (kg ha^{-1}), 771–1821 (kg ha^{-1}), and 1640–2584 (kg ha^{-1}), respectively. Observed rye and radish biomass ranges reported in that study differed from our study likely due to variation in location, weather, cash crop N management, and cover crop management.

4.2. Impact of nitrogen application timing and zero control on tile NO_3-N losses

In the UMRB, a consistent emphasis has been placed on transitioning fall-applied N to the spring as pre-plant or side-dress applications closer to the timing of peak N demand of corn to reduce the susceptibility of N loss from agricultural fields (Illinois Nutrient Loss Reduction Strategy, 2015; Ribaudo et al., 2012). In our study, this transitioning of fall-applied N to the spring resulted in an 11% reduction in flow-weighted NO_3-N and a 25% increase in NO_3-N load over a three-year period. This trend of variability in NO_3-N load reductions between fall and spring N management is consistent with the literature that suggests switching from a fall N system to a majority spring N system results in a −67 to 52% reduction in NO_3-N load via tile drainage, with an average of 9.3% (Randall et al., 2003; Randall and Vetsch, 2005; Randall and Mulla, 2001; Dinnes, 2004; Rejesus and Hornbaker, 1999). Specifically, in our study, when considering NO_3-N load, we observed 66% greater NO_3-N load for the spring dominated nitrogen treatment compared to the fall dominated nitrogen treatment during the soybean. This trend is corroborated by other tile-drainage studies within the UMRB that found 32% less and 88% greater N load for spring N versus fall N during soybean years (Randall and Vetsch, 2005; Pittelkow et al., 2017). These observations indicate that in spring N systems, reductions in excessive NO_3-N leaching could be attributed to a timely N application and corn N uptake. However, in the subsequent fallow period and soybean growing season a significant mass of residual N loss occurs via tile drainage when N fertilizer is applied in the spring (Randall and Vetsch, 2005; Pittelkow et al., 2017). Additionally, our data agree with the literature and confirms that switching N application timing alone is not adequate to achieve N load reductions in the UMRB that could lead to a significant reduction in the size of the Gulf of Mexico Hypoxic Zone.

One of the unexpected observations from our study was the fact that NO_3-N loading via tile-drainage was similar for the zero control that did not receive N fertilizer to both the fall dominated nitrogen and spring dominated nitrogen that received the full rate of N fertilizer. Contributing factors to this finding may be differences in corn yield and N uptake between the zero control and fertilized treatments. Fertilized plots resulted in an average of 2.5 times greater corn yield then the zero control (Table 5). It is likely that unfertilized corn plants resulted in less evapotranspiration and exerted less physical demand on the NO_3-N in the soil solution due to poor N nutrition and root development. Furthermore, the soil at the experimental site had an average soil organic matter of 3.4%, which could be contributing to increased inorganic N within the soil solution.

4.3. Impact of cover crop inclusion on spring and fall N application systems

In our study, combining a spring N application with cover crops resulted in a 39% and 47% reduction in NO_3-N flow-weighted concentration and load, respectively. These reductions were consistent with what was observed in the literature, where cover crops in spring N application systems reduced flow-weighted NO_3-N concentration by 30–59% (Kaspar et al., 2007; Kaspar et al., 2012; Drury et al., 2014) and NO_3-N load by 12–61% (Strock et al., 2004; Kaspar et al., 2007, 2012; Drury et al., 2014). With the exception of Strock et al. (2004), who reported that rye reduced flow-weighted NO_3-N concentrations by 13% over a 3-year period, which was drastically lower due to the application of cover crops only after corn.

To address N loading from Fall N application, which is common in the UMRB, one objective our study was to compare the effectiveness of augmenting a fall N application system with cover crops to a fall N system without cover crops. We observed that CC reduced the mean annual flow-weighted NO_3-N concentrations of tile water by 38% and NO_3-N load by 40% when added to a fall N application system. To the authors' knowledge, the data presented in this study represent the only report of the impact of CC on tile NO_3-N in fall N application systems. However, these reductions are similar to those in spring N application systems reported in both this study and the literature. Suggesting that, despite N application timing, cover crops are effective at reducing tile N losses.

Additionally, we found that NO_3-N reductions, due to cover crops, occurred across the entire hydrologic year (Fig. 2b and c), demonstrating that the impact of CC on water quality is not limited only to the CC growing season. Moreover, unlike N application timing, CC inclusion resulted in water quality benefits in years where N was not applied. For example, we observed an average reduction of 37% in the soybean year, which is similar to 42% reported by Kaspar et al. (2007). This annual impact of CC on N loading could be attributed N cycling, where CC are altering the concentration and distribution of available N in the soil profile making a smaller mass of NO_3-N susceptible to loss through tile drainage (Lacey and Armstrong, 2014; Johnson et al., 1998). In our study, an example of N cycling is that on average we found a 2:1 ratio of CC shoot N relative to N that cover crops prevented from leaving via tile-drainage. This is a conservative measure of CC N cycling potential because it is not considering the N that is in the CC roots. Moreover, both CC treatments reduced N loading by 66% on average relative to the zero control. This indicates that CC are potentially absorbing naturally mineralized N that contributes to N loss via tile-drainage.

Adjusting the N application timing from fall to spring application of N and cover cropping have both demonstrated the potential to be effective N loss reduction methods. Combination the two methods reduced flow-weighted NO_3-N concentrations by 39%. However, the spring dominated nitrogen with cover crop treatment only resulted in an average reduction of 46% in NO_3-N concentration relative to the fall dominated nitrogen treatment (Fig. 2d). This suggests that, while not additive, the combination of spring N application timing and cover cropping does result in increased efficacy to reduce NO_3-N losses through agricultural subsurface drainage systems.

Despite the long-standing effort to encourage farmer adoption of spring N application systems in the UMRB, there are many watersheds in the region where it is a common practice for a significant mass of N to be fall applied as anhydrous ammonia, ammonium phosphate, and manure (Bierman et al., 2012; Illinois Nutrient Loss Survey Results, 2016; Lemke et al., 2011; Ribaudo et al., 2012; Smiciklas et al., 2008). Results of this study demonstrated that applying fall N into a living CC stand resulted in a 30% and 52% reduction in NO_3-N concentration and load relative to applying N in the spring without the presence of CC. This observation suggests that augmenting a fall N system with CC could be an effective adaptive BMP that reduces the susceptibility of N loading via tile drainage in watersheds dominated by fall-applied N.

5. Conclusion

The results of this study confirmed that right timing of N application alone results in a variable impact on N loading via tile drainage and that coupling in-field N reduction practices are most effective. Adoption of a CC mixture allows for responsive cover crop growth in the event of abnormal increases in air temperature and precipitation in the fall or spring that results in ideal conditions for N losses through tile drainage. Zero application of fertilizer N resulted in similar NO_3-N loading compared to fall and spring N management systems without cover crops; however, augmenting those systems with cover crops drastically reduced N loss when compared to the non-fertilized plots. The presence of cover crops reduced corn yields but did not affect soybean yields. The inclusion of CC was an effective NO_3-N loss mitigation strategy, regardless of the N fertilizer application timing. Finally, CC proved to be effective in reducing NO3-N loading through tile-drainage across the spectrum of N fertilizer management systems common to the UMRB.

Funding

This work was supported by the Illinois Nutrient Research and Education Council [grant number 11580-02-502009170].

Acknowledgements

The authors would like to thank the collaborating producer for performing all in-field applications. Also the authors acknowledge Travis Deppe, Felix Vogel, Victoria Heath, and Clayton Nevins for their time in sample collection, preparation and analysis.

References

Basche, A.D., Kaspar, T.C., Archontoulis, S.V., Jaynes, D.B., Sauer, T.J., Parkin, T.B., Miguez, F.E., 2016. Soil water improvements with the long-term use of a winter rye cover crop. Agric. Water Manag. 172, 40–50.
Bierman, P.M., Rosen, C.J., Venterea, R.T., Lamb, J.A., 2012. Survey of nitrogen fertilizer use on corn in Minnesota. Agric. Syst. 109, 43–52.
Blesh, J., Drinkwater, L.E., 2014. Retention of N-labeled fertilizer in an Illinois prairie soil with winter rye. Soil Sci. Soc. Am. J. 78 (2), 496–508.
Cooper, R.J., Aziza, J.H., Hiscocka, K.M., Lovetta, A.A., Dugdalea, S.J., Sünnenberga, G., Noble, L., Beamish, J., Hovesen, P., 2017. Assessing the farm-scale impacts of cover crops and non-inversion tillage regimes on nutrient losses from an arable catchment. Agric. Ecosyst. Environ. 237, 181–193.
Daigh, A.L., Zhou, X., Helmers, M.J., Pederson, C.H., Ewing, R., Horton, R., 2014. Subsurface drainage flow and soil water dynamics of reconstructed prairies and corn rotations for biofuel production. Vadose Zone J. 13, 1–11.
David, M., McIsaac, G., Czapar, G., Schnitkey, G., Mitchell, C., 2013. Science Assessment to Support an Illinois Nutrient Loss Reduction Strategy.
Dean, J.E., Weil, R.R., 2009. Brassica cover crops for nitrogen retention in the Mid-Atlantic Coastal Plain. J. Environ. Qual. 38 (2), 520–528.
Dinnes, D.L., 2004. Assessments of Practices to Reduce Nitrogen and Phosphorus Nonpoint Source Pollution of Iowa's Surface Waters. USDA-ARS, National Soil Tilth Laboratory, pp. 366.
Drury, C.F., Tan, C.S., Welacky, T.W., Reynolds, W.D., Zhang, T.Q., Oloya, T.O., McLaughlin, N.B., Gaynor, J.D., 2014. Reducing nitrate loss in tile drainage water with cover crops and water-table management systems. J. Environ. Qual. 43 (2), 587–598.
Gardner, J.B., Drinkwater, L.E., 2009. The fate of nitrogen in grain cropping systems: a meta-analysis of 15N field experiments. Ecol. Appl. 19 (8), 2167–2184.
Illinois Nutrient Loss Reduction Strategy, 2015. Illinois Environmental Protection Agency. Accessed 12 Dec. 2017. http://www.epa.illinois.gov/topics/water-quality/watershed-management/excess-nutrients/nutrient-loss-reduction-strategy/index.
Illinois Nutrient Loss Survey Results, 2016. National Agricultural Statistics Service. Accessed 15 Jan. 2018. https://www.nass.usda.gov/Statistics_by_State/Illinois/Publications/Current_News_Release/2016/Nutrient_Loss_Survey_Results.pdf.
Iowa Nutrient Reduction Strategy, 2013. A Science and Technology-based Framework to Assess and Reduce Nutrients to Iowa Waters and the Gulf of Mexico. Iowa Department of Agriculture and Land Stewardship. Iowa Department of Natural Resources, and Iowa State University College of Agriculture and Life Sciences, Ames, IA.
Johnson, T.J., Kaspar, T.C., Kohler, K.A., Corak, S.J., Logsdon, S.D., 1998. Oat and rye overseeded into soybean as fall cover crops in the upper Midwest. J. Soil Water Conserv. 53 (3), 276–279.
Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Moorman, T.B., 2007. Rye cover crop and gamagrass strip effects on NO concentration and load in tile drainage. J. Environ. Qual. 36 (5), 1503–1511.
Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Moorman, T.B., Singer, J.W., 2012. Effectiveness of oat and rye cover crops in reducing nitrate losses in drainage water. Agric. Water Manag. 110, 25–33.
Lacey, C.G., Armstrong, S.D., 2014. In field measurements of nitrogen mineralization following fall applications of N and the termination of winter cover crops. Air Soil Water Res. 7, 53.
Lacey, C., Armstrong, S., 2015. The efficacy of winter cover crops to stabilize soil inorganic nitrogen after fall-applied anhydrous ammonia. J. Environ. Qual. 44 (2), 442–448.
Lemke, A.M., Kirkham, K.G., Lindenbaum, T.T., Herbert, M.E., Tear, T.H., Perry, W.L., Herkert, J.R., 2011. Evaluating agricultural best management practices in tile-drained subwatersheds of the Mackinaw River, Illinois. J. Environ. Qual. 40 (4), 1215–1228.
Minnesota Nutrient Reduction Strategy, 2014. Minnesota Pollution Control Agency. Accessed 10 Jan. 2018. https://elibrary.asabe.org/azdez.asp?search=0&JID=1&AID=47346&CID=ids2016&v=&i=&T=2.
Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008. Gulf Hypoxia Action Plan 2008 for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin. Washington, DC. .
Missouri Nutrient Loss Reduction Strategy, 2014. Missouri Department of Natural Resources. Accessed 10 Jan. 2018. https://dnr.mo.gov/env/wpp/mnrsc/docs/nlrs-strategy-2014.pdf.
Pittelkow, C.M., Clover, M.W., Hoeft, R.G., Nafziger, E.D., Warren, J.J., Gonzini, L.C., Greer, K.D., 2017. Tile drainage nitrate losses and corn yield response to fall and spring nitrogen management. J. Environ. Qual. 46 (5), 1057–1064.
Qi, Z., Helmers, M.J., 2010. Soil water dynamics under winter rye cover crop in central Iowa. Vadose Zone J. 9 (1), 53–60.
Randall, G.W., Mulla, D.J., 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. J. Environ. Qual. 30 (2), 337–344.
Randall, G.W., Vetsch, J.A., 2005. Nitrate losses in subsurface drainage from a corn–soybean rotation as affected by fall and spring application of nitrogen and nitrapyrin. J. Environ. Qual. 34 (2), 590–597.
Randall, G.W., Vetsch, J.A., Huffman, J.R., 2003. Nitrate losses in subsurface drainage from a corn–soybean rotation as affected by time of nitrogen application and use of nitrapyrin. J. Environ. Qual. 32 (5), 1764–1772.
Rejesus, R.M., Hornbaker, R.H., 1999. Economic and environmental evaluation of alternative pollution-reducing nitrogen management practices in central Illinois. Agric. Ecosyst. Environ. 75 (1), 41–53.
Ribaudo, M., Livingston, M., Williamson, J., 2012. Nitrogen Management on Us Corn Acres, 2001–10. United States Department of Agriculture, Economic Research Service.
Smiciklas, K.D., Moore, A.S., Adams, J.C., 2008. Fertilizer nitrogen practices and nitrate levels in surface water within an Illinois watershed. J. Nat. Resour. Life Sci. Educ. 37 (1), 14–19.
Smil, V., 1999. Nitrogen in crop production: an account of global flows. Global Biogeochem. Cycles 13 (2), 647–662.
Strock, J.S., Porter, P.M., Russelle, M.P., 2004. Cover cropping to reduce nitrate loss through subsurface drainage in the northern US Corn Belt. J. Environ. Qual. 33 (3), 1010–1016.
White, C.M., Weil, R.R., 2010. Forage radish and cereal rye cover crop effects on mycorrhizal fungus colonization of maize roots. Plant Soil 328 (1-2), 507–521.
Wisconsin Nutrient Reduction Strategy, 2013. Wisconsin Department of Natural Resources. Accessed 10 Jan. 2018. https://dnr.wi.gov/topic/SurfaceWater/nutrient/combined_draft.pdf.