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Long-Term Effects of Poultry Manure Application on Nitrate Leaching in Tile Drain Water

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Abstract

A long-term study (1998 to 2009) was initiated on eleven tile-drained field plots, ranging in size from 0.19 to 0.47 ha, to investigate the effects of poultry manure application on subsurface drainage water quality in Iowa under a corn-soybean rotation system. The experimental treatments included poultry manure at rates of 168 kg N ha-1 (PM) and 336 kg N ha-1 (PM2), each with three replications; nitrogen application from chemical fertilizer, urea ammonium nitrate (UAN), at a rate of 168 kg N ha-1 with four replications; and a control treatment that received 0 kg N ha-1. Subsurface drainage (tile) flow volume was monitored, and drainage samples were collected and analyzed for nitrate-nitrogen (NO3-N). The results from this 12-year study show that NO3-N losses with tile drainage were more likely to occur during the early stages of crop production (April to June) and were more related to the monthly distribution of precipitation than the total rainfall amount. The overall results of this study indicate that applying poultry manure at 168 kg N ha-1 resulted in significantly lower flow-weighted nitrate concentrations (PM < UAN < PM2) and the lowest nitrogen losses to subsurface drain water compared to UAN and PM2 application(PM < UAN < PM2), as well as higher crop yields compared to UAN application. Therefore, it can be concluded that poultry manure application at a rate of 168 kg N ha-1 is an environmentally sound N application practice with good yield potential for corn and soybean production systems with poorly drained soils in the upper Midwest. Future work is recommended to identify new practices and technologies to reduce nitrate loss to water systems.

Keywords

Statistics, Corn-soybean rotation, Nitrate leaching, Poultry manure, Tile drainage

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Statistics and Probability

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LONG-TERM EFFECTS OF POULTRY MANURE APPLICATION ON NITRATE LEACHING IN TILE DRAIN WATER

H. Q. Nguyen, R. S. Kanwar, N. L. Hoover, P. Dixon, J. Hobbs, C. Pederson, M. L. Soupir

ABSTRACT. *A long-term study (1998 to 2009) was initiated on eleven tile-drained field plots, ranging in size from 0.19 to 0.47 ha, to investigate the effects of poultry manure application on subsurface drainage water quality in Iowa under a corn-soybean rotation system. The experimental treatments included poultry manure at rates of 168 kg N ha^{-1} (PM) and 336 kg N ha^{-1} (PM2), each with three replications; nitrogen application from chemical fertilizer, urea ammonium nitrate (UAN), at a rate of 168 kg N ha^{-1} with four replications; and a control treatment that received 0 kg N ha^{-1}. Subsurface drainage (tile) flow volume was monitored, and drainage samples were collected and analyzed for nitrate-nitrogen (NO_3-N). The results from this 12-year study show that NO_3-N losses with tile drainage were more likely to occur during the early stages of crop production (April to June) and were more related to the monthly distribution of precipitation than the total rainfall amount. The overall results of this study indicate that applying poultry manure at 168 kg N ha^{-1} resulted in significantly lower flow-weighted nitrate concentrations (PM < UAN < PM2) and the lowest nitrogen losses to subsurface drain water compared to UAN and PM2 application(PM < UAN < PM2), as well as higher crop yields compared to UAN application. Therefore, it can be concluded that poultry manure application at a rate of 168 kg N ha^{-1} is an environmentally sound N application practice with good yield potential for corn and soybean production systems with poorly drained soils in the upper Midwest. Future work is recommended to identify new practices and technologies to reduce nitrate loss to water systems.*

Keywords. *Corn-soybean rotation, Nitrate leaching, Poultry manure, Tile drainage.*

During the last ten years, Iowa has been leading the nation in the production of many agricultural commodities, including corn, soybeans, and eggs (USDA-NASS, 2010). The steady growth of these industries has created challenges regarding proper treatment and disposal of poultry (*Gallus gallus domesticus*) manure and litter. In 2007, Iowa egg production generated approximately 2.3 million Mg of poultry manure. Land application of poultry manure for corn production may be an environmentally and economically sound solution for Iowa and other egg and poultry producing regions in the U.S. (Chambers et al., 2006; Edwards and Daniel, 1992; Edwards et al., 1996; Shepherd, 1993; Moore et al., 1995; Sharpley et al., 1998). Poultry manure is a great source of fertilizer to enhance crop production; however, there are potential environmental issues associated with the utilization of poultry manure as fertilizer, including overapplication due to limited land available for disposal and the cost of transportation (Edwards and Daniel, 1992; Shepherd, 1993; Moore et al., 1995; Sharpley et al., 1998). In Iowa and several other states in the U.S. Corn Belt, surface application of poultry manure has also been associated with nitrate leaching via subsurface drainage systems under cropped fields (Baker and Johnson, 1981; Zucker and Brown, 1998; Bakhsh et al., 2002). Nearly 50% of agricultural farm land in Iowa is equipped with artificial subsurface drainage to lower the water table below the root zone and enhance crop production (Weed and Kanwar, 1996; Kladivko et al., 2004).

Several studies have documented the fate and transport of nutrients, such as nitrogen and phosphorus, from agricultural land via tile drainage systems, which contribute to impaired water quality in lakes, streams, and rivers (Edwards and Daniel, 1992; Sharpley et al., 1998; De Vos et al., 2000; Dinnes et al., 2002). Adams et al. (1994) investigated the effects of different poultry manure application rates to fescue plots on nitrate concentrations at various depths within the vadose zone. Wood et al. (1996) also observed the increase of nitrate leaching into tile drains from corn plots with a long-term history of poultry manure application. Nitrate-N (NO_3-N) loss with tile drain water has been found to peak in early spring when the crop plants are small, while the NO_3-N loss decreases sharply during the growing season due to reduced tile flow and increased crop N uptake (Sharpley and Syers, 1979; Rossi

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et al., 1991; Sims and Wolf, 1994). To reduce NO_3-N leaching effectively, many studies suggest that long-term N application rates should closely match crop nutrient requirements (Hansen and Djurhuus, 1996; Blackmer et al., 1997; Kirchmann et al., 2002; Van Es et al., 2006).

Quantification of nitrate leaching from cropping systems amended with poultry manure is needed to optimize the poultry manure application rates and inform the land management practices needed to mitigate the environmental impacts of poultry manure application. More commonly published short-term (two to three years) studies investigating the impacts of poultry manure on water quality may not account for variable weather conditions over multiple years, especially when the experiments are conducted during dry or wet periods (Randall, 1998; Orecroft et al., 2000; Randal and Mulla, 2001; Kladivko et al., 2004). Longer-term studies have the advantage of being able to assess changes in soil characteristics, cropping systems, land management practices, and weather conditions (including rainfall intensity and seasonal effects) on nitrate leaching patterns and nutrient dynamics of the system (Cabrera et al., 1993; Cooperband et al., 2002; Rossi et al., 1991; Shepherd, 1993; Sharpley, 1997; Moore and Edwards, 2007; Harmel et al., 2009).

Water quality data from subsurface drainage systems in Iowa are limited, especially long-term (>10 years) studies. Therefore, a 12-year field study was initiated to provide insight into the impacts of land-applied poultry manure on crop yield and subsurface water quality. The objectives of this study are to (1) evaluate the effects of different fertilizer application rates and N sources (poultry manure and UAN) on crop yield, tile drainage flow, and NO_3-N concentration and losses; and (2) compare temporal changes in trends of nitrate losses in tile drain water in response to different N treatment inputs. The hypotheses of the study are (1) applying poultry manure at the same rate as N chemical fertilizer may yield equal or less NO_3-N concentration and losses in tile drain water, and (2) increasing the application rates of poultry manure over the crop requirements may increase nitrate loss in subsurface drainage water. This work will be useful in establishing recommended practices for poultry manure application to land under corn and soybean production as well as promoting a sustainable eco-agricultural system and poultry/egg industry in Iowa.

Materials and Methods

Experimental Site and Monitoring Equipment Description

Field experiments were conducted from 1998 to 2009 at Iowa State University's Agronomy and Agricultural Engineering Research Center near Ames, Iowa. The site is located on soils with a Canisteo-Clarion-Nicollet association, which includes a combination of Nicollet, Clarion, Canisteo, and Harps loam soils formed in glacial till under prairie vegetation with characteristic organic matter (OM) content ranging from 3% to 8% based on soil type (USDA-SCS, 1981). Topsoil (0-30 cm) measurements for all plots in 2006 indicate lower than expected OM, ranging from 2.6% to 4.2%, with a mean value of 3.4%. This soil association is characterized as having very poor natural drainage, which benefits from subsurface tile drainage (USDA-SCS, 1981). The long-term monitoring study was conducted on eleven field plots (ranging from 0.19 to 0.47 ha) with a single subsurface tile drain in the middle of each plot (fig. 1). The tile drains were intercepted at the end of each field plot, and a V-notch and sump were installed for subsurface drain water monitoring and water quality sampling for all treatment plots. Drainage monitoring equipment was installed in the check plot in 2000. Every fall, half of each field plot (where corn was grown in the previous year) was tilled using a chisel plow, which ensured that approximately 30% of the crop residue was left on the surface, and was planted to soybean (Kruger 2426). The other half of the same plot was planted to corn (Dekalb 580), with the crops rotated annually over the 12-year study period (1998-2009). Nitrogen treatment was applied at the current recommended N rate for corn production under a corn-soybean rotation in Iowa of 168 kg N ha^{-1} to the half of each field plot planted to corn (Blackmer et al., 1997; Sawyer et al., 2002). Poultry manure was applied at two different rates (168 and 336 kg N ha^{-1}), and liquid 28% urea ammonium nitrate (UAN) was applied at a rate of 168 kg N ha^{-1}. Both poultry manure and UAN were applied to field plots by surface broadcast and incorporated into the soil by tilling to a depth of approximately 15 cm to reduce nitrogen loss via

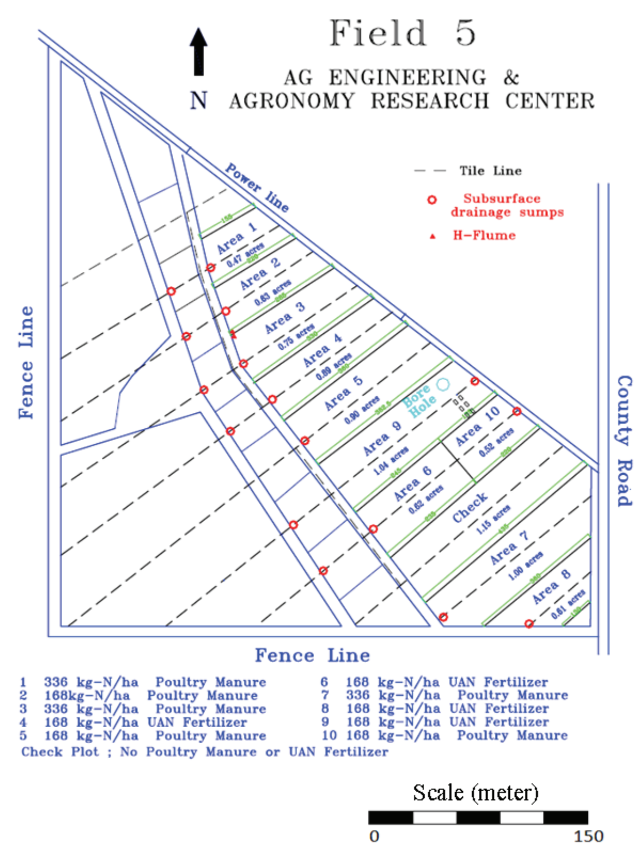

Figure 1. Diagram of field 5 at the Iowa State University Agronomy Research Center (adapted from Cheatham, 2003).

Table 1. Field plot management and fertilizer application, 1998-2009.

Year	Apply Manure	Apply UAN	Plant[a] Corn	Plant[a] Soybean	Harvest Corn	Harvest Soybean
1998	Apr. 29	May 1	May 8	May 8	Oct. 19	Sept. 30
1999	May 4	May 4	May 10	May 10	Oct. 14	Oct. 12
2000	Apr. 13	May 5	May 8	May 8	Sept. 20	Oct. 4
2001	May 17	May 17	May 18	May 18	Oct. 15	Oct. 17
2002	May 3	May 3	May 22	May 22	Oct. 18	Oct. 15
2003	May 16	May 16	-	-	Oct. 9	Sept. 25
2004	Apr. 28	Apr. 29	May 3	May 11	Oct. 8	Sept. 27
2005	May 10	May 10	-	-	Oct. 14	Oct. 10
2006	May 15	May 15	-	-	Oct. 23	Oct. 25
2007	May 21	May 21	-	-	Oct. 30	Oct. 30
2008	May 22	May 22	May 22	May 22	Oct. 27	Oct. 20
2009	May 12	May 12	May 14	May 14	Oct. 12	Sept. 30

[a] Planting dates were not recorded in 2003 and 2005-2007.

volatilization. A control plot, designated as the check plot (fig. 1), was established with 0 kg N ha^{-1} for comparison purposes. Various agronomic activities conducted at the research field for each year are presented in table 1. More details on field activities can be found in the previously published work of Chinkuyu et al. (2002).

Poultry Manure and Water Quality Sample Collection and Analysis

Three representative poultry manure samples were collected before field application each year and sent to MTVL Laboratories, Inc., in Nevada, Iowa, for analysis of N, P, and K to determine the actual poultry manure application rates. Subsurface flow volume was measured and recorded using a HOBO Pendant Event Data Logger (Onset Computer Corp., Pocasset, Mass.) connected to a Trion water meter register. The logger recorded a time stamp with each switch closure every time one cubic foot (or 0.0283 m^3) of water passed through the Neptune T-10 water meter. Water samples were collected twice a week and/or after rainfall events of more than 5 cm from each field plot in most years. Water samples were analyzed for NO_3-N on a Lachat autoanalyzer at Iowa State University's Agriculture and Biosystems Engineering Water Quality Research Laboratory (WQRL) using the cadmium reduction method (Lachat Instruments, Milwaukee, Wisc.). Subsurface drainage water flow measurements were made from mid-March to October if subsurface drains were flowing.

Experimental Design and Data Analysis

Eleven field plots were used in this experiment, with corn and soybeans grown on opposite halves of each plot. Corn and soybean crops were rotated within each plot annually for 12 years (1998-2009). One of four nitrogen treatments, including poultry manure (168 or 336 kg N ha^{-1}), UAN (168 kg N ha^{-1}), and a control (0 kg N ha^{-1}), were applied to the half of the field plots where corn was grown. The experimental treatments were arranged in a completely randomized design with unbalanced replications due to the lack of land available for field plots.

Statistical analysis of the 12-year study's data was conducted for corn and soybean yield, tile flow, and NO_3-N concentration and losses in tile water based on methods used in previous studies (Kaspar et al., 2007; Bakhsh et al., 2010). Since multiple measurements were made on the same plots over a 12-year period, the MIXED procedure with repeated measures (Littell et al., 1998) was used for statistical analyses of the data (SAS, 2009). A mixed linear model incorporated coefficients for the long-term trends for source of treatment, year, and rainfall, while the variability of each plot throughout the 12-year study was treated as a random effect for the evaluation of tile flow volume, NO_3-N concentrations, and NO_3-N losses. Appropriate transformations of the data, which included square root of tile flow and natural log of NO_3-N concentration, were made to maintain approximately equal variances for all data types to meet the assumptions for statistical analysis.

The statistical analysis was conducted separately for corn and soybean yield data using the GLM procedure, with comparison of LSMEANS (SAS, 2009). Subsurface drainage samples could not be collected for two of the UAN plots (plots 6 and 9); therefore, these plots were excluded from statistical analysis for tile flow and tile drainage NO_3-N concentration. Data on monthly tile flow volumes were normalized to equal 0.1 ha areas for better statistical comparisons. In all of the statistical analyses, *a priori* $\alpha = 0.05$ probability levels were used.

Results and Discussions

Poultry Manure Characteristics and Application Rates

Poultry manure analyses found that nutrient (N, P, and K) and solid matter contents in the manure were highly variable from year to year. Based on the chemical analyses of the poultry manure, N application rates for each year were calculated and are presented in table 2. The high variability in the nutrient content of poultry manure over time reveals the difficulties that existed in trying to achieve the target application rate of 168 kg N ha^{-1}. The moisture content of the poultry manure in this study ranged from 25% to 76%, which may have contributed to the high variability of N and P content in the poultry manure over the years and the resulting highly variable manure application rates, as discussed in depth by Harmel et al. (2011).

On average, the actual N application rates for the PM and PM2 treatments were 179 and 354 kg N ha^{-1}, respectively, when averaged over the 12-year study period. The N application rate was low in 2000 because a 10% carryover N credit was allowed from manure application in 1998. An additional N credit of one kg per 60 kg of soybean yield from 1999 was assumed to be available for the corn crop in 2000. When the calculated carryover N credits were applied to each plot in addition to the actual N application, the target application rates of 168 and 336 kg N ha^{-1} were exceeded, with 158 kg ha^{-1} (PM) and 393 kg ha^{-1} (PM2). After the year 2000, the N credit carryover approach was eliminated and actual application of N from poultry manure was considered. The average N and P application rates (table 2) show that the N: P ratio was not balanced from year to year for the PM and PM2 treatments, which may result in P buildup in the soil or P leaching to subsurface drain water when applied on an N basis.

Table 2. Annual application rates of poultry manure on field plots, 1998-2009.

Year	PM Treatment (168 kg N ha^{-1})				PM2 Treatment (336 kg N ha^{-1})			
	Average Manure Application Rate[a] (Mg ha^{-1})	Average Application Rate (kg ha^{-1})			Average Manure Application Rate[a] (Mg ha^{-1})	Average Application Rate (kg ha^{-1})		
		N[b]	P	K		N[b]	P	K
1998	10.6	114	81	115	23.2	250	165	225
1999	9.9	214	328	172	15.0	317	472	208
2000	3.2	83	128	79	8.9	314	333	199
2001	9.0	185	244	181	15.3	314	416	308
2002	8.1	125	87	49	14.5	225	156	88
2003	11.6	203	158	123	18.6	328	255	198
2004	10.4	236	217	117	20.5	468	431	232
2005	8.9	177	540	278	16.7	333	1019	524
2006	9.2	175	233	108	17.0	324	433	200
2007	9.6	162	95	133	19.5	328	193	269
2008	8.5	174	174	96	16.0	326	326	181
2009	6.6	170	124	115	13.3	344	250	231
Average	8.8	177	212	138	16.5	338	388	251
SD	2.2	51	141	64	3.7	59	238	105

[a] Manure application rates are reported "as is", without corrections for moisture content.

[b] Values show a 5% N loss at application. 1998 and 1999 represent 75% N availability assumed during first year of manure application.

Table 3. Precipitation during the study period, 1998-2009.

Year	Month								Growing Season (May-Sept.)	Drainage Season (March-Oct.)
	March	April	May	June	July	August	September	October		
1998	71	81	92	274	68	94	24	102	552	806
1999	25	207	150	185	162	151	61	9	709	949
2000	11	21	120	104	72	34	26	50	356	437
2001	28	96	190	50	48	74	149	65	511	700
2002	10	95	130	81	150	209	38	79	606	790
2003	29	112	122	150	168	25	100	24	565	730
2004	96	61	208	91	50	132	34	45	515	717
2005	35	82	111	124	104	172	111	9	622	748
2006	74	109	55	21	141	156	191	63	564	811
2007	81	153	169	52	75	200	48	137	545	915
2008	71	130	216	271	234	53	78	92	852	1145
2009	103	116	102	104	70	123	24	186	424	829
Average	53	105	139	125	112	119	74	72	568	798
Normal	54	89	108	129	106	102	87	65	532	740

Site Precipitation and the Effects of Precipitation on Subsurface Drainage

Precipitation data from the Iowa State University Agriculture Engineering Farm weather station (Iowa Environment Mesonet) were recorded daily, and the monthly precipitation values are presented in table 3. The long-term average precipitation for Ames, Iowa (1961 to 1990) was 740 mm between March and October. During the 12-year study period (1998 to 2009), the average precipitation at the experimental site was 798 mm, which was about 8% above the long-term average. For four years (1999, 2007, 2008, and 2009), the average precipitation measurements of 949, 915, 1145, and 829 mm, respectively, were higher than the normal precipitation. Seven of the 12 years had precipitation within 10% of the normal precipitation. Comparison of monthly average precipitation data revealed that in the months of April, May, and August, the monthly precipitation amounts were higher than the long-term average. The higher than normal amounts of rainfall measured in April and May likely resulted in higher tile flow volumes and nitrate losses with tile drain water, which may require innovative management practices to protect water resources (Randal and Iragavarapu, 1995; Randall and Vetsch, 2005).

The subsurface drainage volume from the field plots was normalized by area for statistical comparison among treatments. As expected, the variation of precipitation patterns considerably affected the variation in tile flow volumes at both yearly and monthly levels (table 4). Figure 2 presents the effects of precipitation on tile flow over the 12-year study period. Tile flows were lowest in 2000, the driest rainfall year, and highest in 2008, the wettest year, which correlated with annual precipitation. The control treatment yielded the highest annual average tile flow (13.3 cm year^{-1}), which is likely due to reduced evapotranspiration caused by reduced crop development and yields from reduced nutrient application. On average, tile flows from the PM2 and UAN treatments were not

Table 4. Average tile flow volume (mm) across all treatments by year and month.

Year	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Total
1998	2	33	31	96	41	0	0	0	203
1999	0	44	46	55	6	3	0	0	154
2000	0	0	1	4	0	0	0	0	5
2001	0	3	41	22	2	0	0	0	69
2002	0	0	46	19	10	6	0	0	81
2003	0	0	84	10	46	0	0	0	141
2004	15	47	39	52	1	0	0	0	153
2005	0	24	42	10	7	9	0	0	93
2006	0	23	52	3	1	0	72	75	226
2007	0	0	14	59	10	0	0	0	83
2008	0	63	77	167	50	48	0	0	405
2009	0	51	83	27	3	0	0	10	174
Average	1	24	46	44	15	6	6	7	149

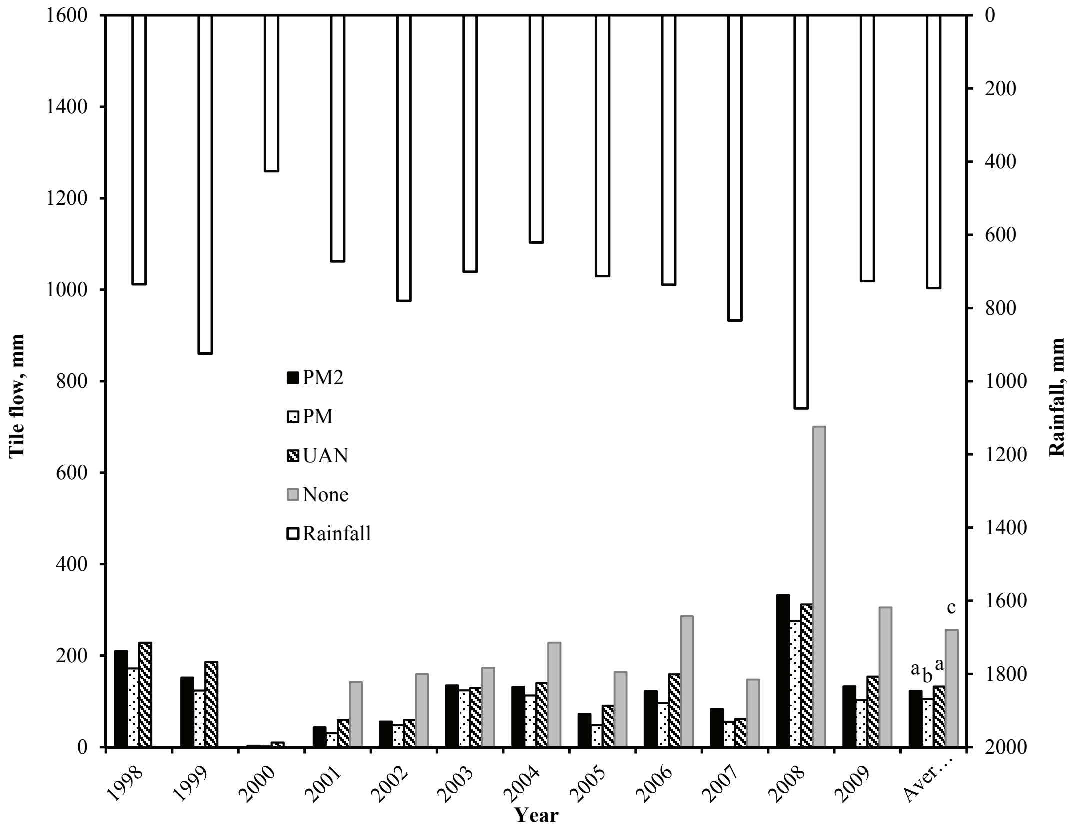

Figure 2. Subsurface drainage (mm) as response to annual precipitation by different N treatments and years. Values followed by the same letters are not significantly different at $\alpha = 0.05$.

significantly different from each other ($p = 0.057$). Analysis of monthly data revealed that seasonal distribution of rainfall had significant impacts on tile flow.

High monthly tile flow variability was observed for all N treatments. Similar spatial variability in tile flow was observed in previous studies, with this variability attributed to changes in soil characteristics following long-term cultivation with different crop rotations and N sources (Adams et al., 1994; Bjorneberg et al., 1998; Kladivko et al., 2004). For example, Kladivko et al. (2004) found that there was no difference in tile flow volume between corn and soybean years during a six-year study period because each year had a different combination of rainfall timing, intensity, and amounts. Kladivko et al. (2004) reported that timing of precipitation had a larger impact on subsurface drainage volume and NO_3-N export in subsurface drainage, especially due to the cycle of wet-dry-normal weather conditions in the Midwestern U.S. Several studies on nitrate leaching have reported that variation in NO_3-N concentration and losses may not be closely associated with daily subsurface drain flows but rather with seasonal variation in tile flow (Randall and Mulla, 2001; Dinnes et al., 2002; Kanwar et al., 2005; Jaynes and Colvin, 2006; Bakhsh et al., 2010; Lawlor et al., 2008). For instance, Bakhsh et al. (2010) concluded that precipitation patterns during the growing season were the main factor contributing to NO_3-N export due to higher tile flow volumes in the early stages of crop growth. Bjorneberg et al. (1996) reported the seasonal effects on tile flow in subsurface drainage systems with higher flows occurring prior to N fertilizer applications.

EFFECTS OF N TREATMENTS ON TILE DRAIN FLOW

Subsurface drain flow did not occur during all months in a given year and was highly variable from plot to plot. The average annual tile flows under different N treatments were 12.3 cm (PM2), 9.9 cm (PM), 13.3 cm (UAN), and 25.6 cm (control). For all years, the PM treatment had significantly lower tile flow in comparison to others treatments under different weather cycles (wet, dry, and normal conditions). Although not statistically significant, poultry manure applied at twice the agronomic application rate (PM2) resulted in lower tile flow compared to plots receiving chemical fertilizer (UAN) treatment and the control treatment (None), but the NO_3-N losses with subsurface drain water were significantly higher from PM2 compared to the other N treatments (fig. 3). Since tile flow and nitrate losses are linearly correlated, using poultry manure for corn-soybean rotation production at higher N rates may increase nitrate losses (Randal, 1998; Rossi et al., 1991; Shepherd, 1993; Kanwar et al., 2005). For example, Kirchmann et al. (2002) suggested that reducing the tile flow volume may reduce the amount of nitrate exported from agricultural land. Bjorneberg et al. (1996) found a strong linear relationship between NO_3-N losses with the changes in tile flow during the crop growing season, as

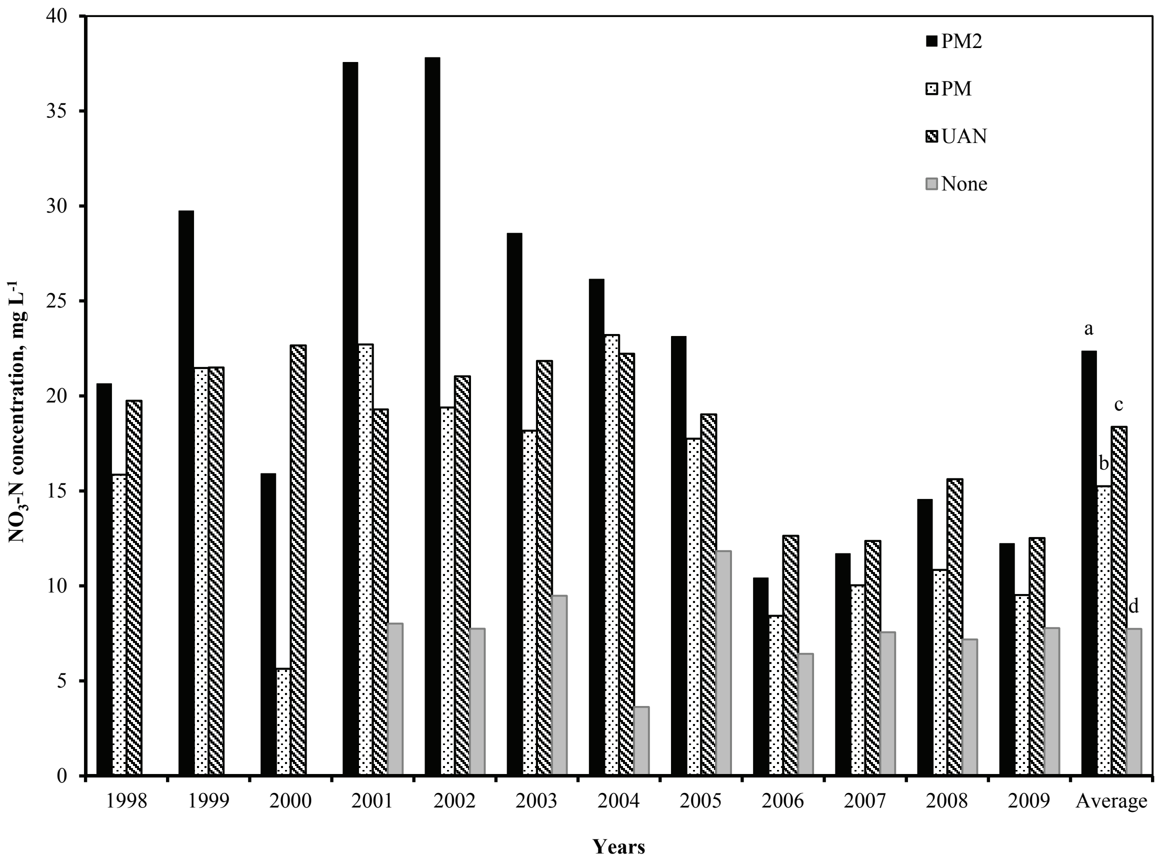

Figure 3. Annual flow-weighted NO_3-N concentrations as a function of N treatment. Values followed by the same letters are not significantly different at $\alpha = 0.05$.

well as under different tillage systems (chisel plow, moldboard plow, ridge till, and no-till). Durry et al. (1993), Randall and Mulla (2001), and Kanwar et al. (2005) reported that crop rotations and conservational tillage systems may help to reduce the subsurface drainage volume from agricultural lands.

Effects of N Treatments on Nitrate Concentrations in Tile Drain Water

The yearly average flow-weighted NO_3-N concentrations as a function of N treatment are presented in figure 3. The PM treatment resulted in significantly lower NO_3-N concentrations in tile drain water ($p < 0.01$), ranging from 9.5 mg L^{-1} in 2009 to 23.2 mg L^{-1} in 2004 with an average of 15.2 mg L^{-1} over the 12-year study period, compared to the UAN and PM2 treatment. In contrast, the PM2 treatment resulted in the highest NO_3-N concentrations (ranging from 10.4 to 37.8 mg L^{-1} with an average of 22.4 mg L^{-1}) in tile drain water in comparison to PM and UAN treatments ($p < 0.01$). Statistical analysis of the data showed that the combined effects of treatments, monthly distribution of rainfall, and tile flow significantly influenced NO_3-N concentrations in tile drain water. Additional analysis was made to evaluate the effects of the dry year (2000), which resulted in increasing NO_3-N concentrations in the following years (2001 and 2002).

Figure 4 presents the trend of the monthly average flow-weighted NO_3-N concentration from March to October for the 12-year period (1998-2009), illustrating the relationship between N treatments and the monthly variability in rainfall patterns and rates of nitrification as a function of temperature, rate of fertilizer or manure application, and plant uptake. The NO_3-N concentrations increased in June and decreased sharply after July, indicating the use of soil nitrogen by the growing crop. On average, the PM treatment had lower monthly average NO_3-N concentrations in tile drain water compared to the UAN and PM2 treatments. The overall results of this study indicate that applying poultry manure at the lower N rate of 168 kg N ha^{-1} resulted in lower NO_3-N concentrations in tile drainage water than poultry manure applied at 336 kg N ha^{-1} and UAN fertilizer applied at 168 kg N ha^{-1}.

Seasonal and N Treatment Effects on Total Nitrate Losses with Tile Drain Water

Figure 5 shows the cumulative average monthly nitrate loss with tile drain water for each treatment. This figure illustrates clearly that, on average, the PM2 and UAN treatments resulted in nearly twice the nitrate loss with tile water compared to the PM treatment during the crop growing season (April through the end of September). The 12-year average NO_3-N losses with tile drain water were 25.7 ha^{-1} $year^{-1}$ for PM2, 14.7 ha^{-1} $year^{-1}$ for PM, 23.6 ha^{-1} $year^{-1}$ for UAN, and 19.0 kg ha^{-1} $year^{-1}$ for None. The relationship between nitrate concentrations in subsurface

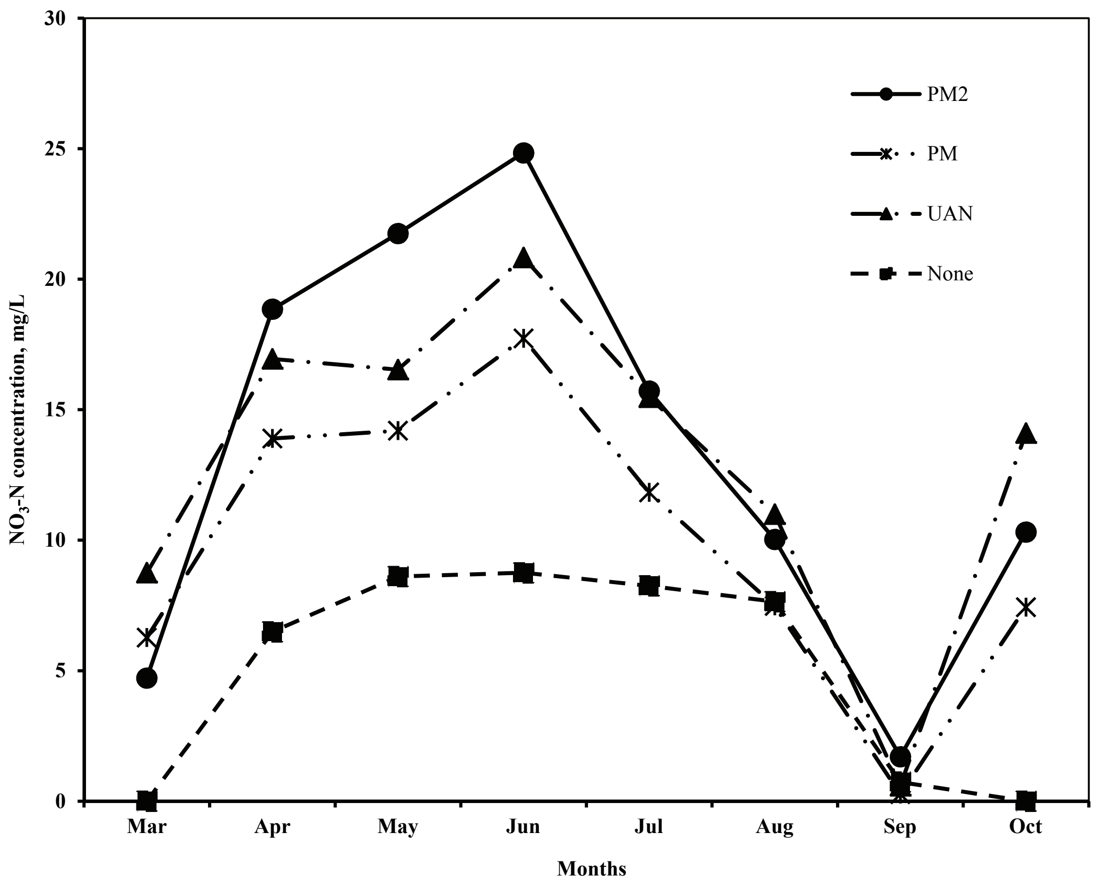

Figure 4. Average (1998-2009) monthly flow-weighted NO_3-N concentrations as a function of N treatment.

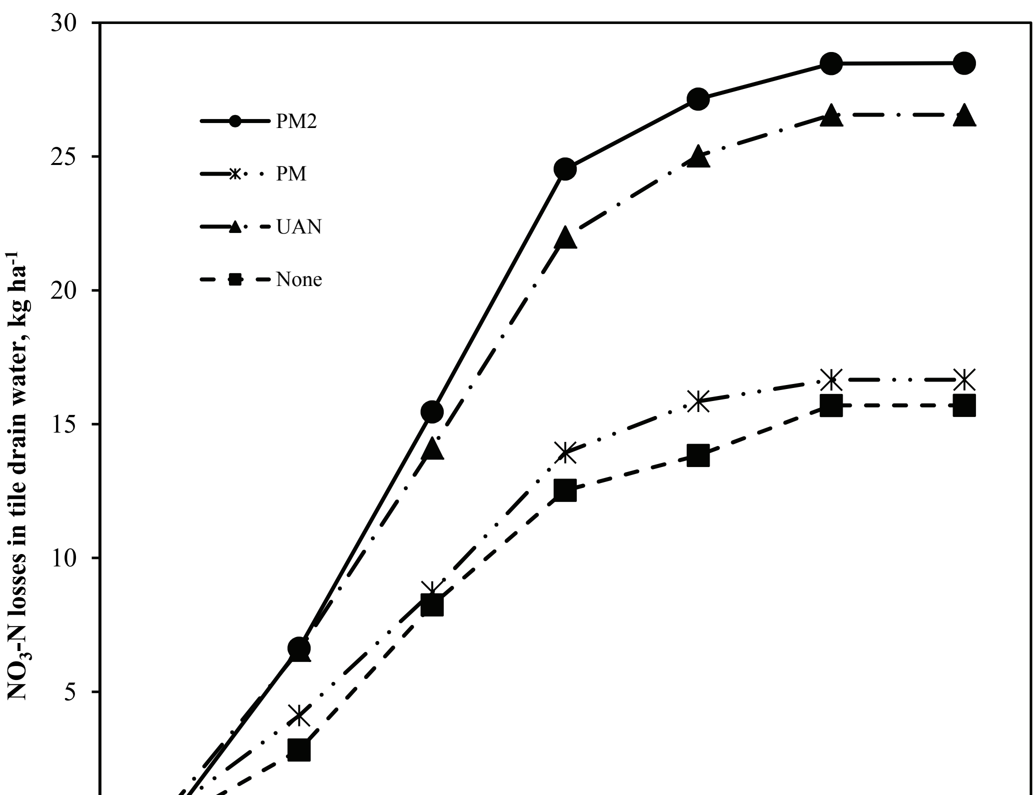

Figure 5. Average (1998-2009) cumulative NO_3-N loss in response to interaction effects of N treatments.

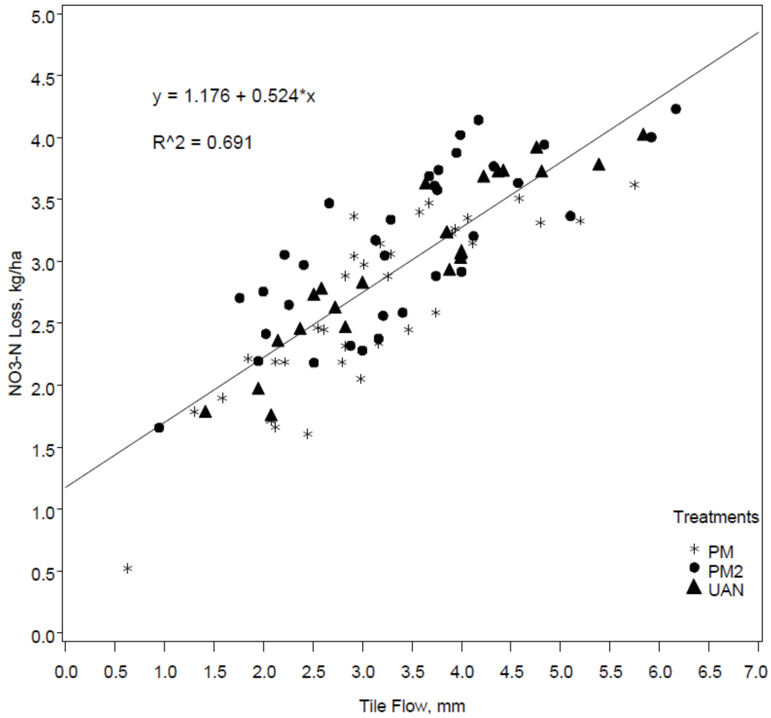

Figure 6. Correlation between NO_3-N loss with subsurface drain water and tile flow.

water and N application rates was not linearly related (R^2 = 0.077). Total seasonal rainfall had a significant effect on the total annual nitrate losses with subsurface tile drain water ($p < 0.05$). Figure 6 demonstrates a linear correlation between the tile flow volume and nitrate loss with tile drain water on an annual basis. Although N application rates from the PM treatment of poultry manure varied (from 87 to 301 kg N ha^{-1}, with a 12-year annual average of 179 kg N ha^{-1}), results of this study clearly show that PM treatment resulted in overall lower nitrate losses compared to the UAN treatment with a similar N application of 168 kg N ha^{-1}.

Many studies conducted to determine the impacts of N fertilizer application rates on NO_3-N leaching with subsurface drainage water have shown that small increases in chemical N fertilizer application rates may greatly increase nitrate export to tile drain water (Baker and Johnson, 1981; Adams et al., 1994; Bergstrom and Kirchmann, 1999; De Vos et al., 2000).

The temporal effects of monthly rainfall variation on NO_3-N loss under different N treatments were also investigated. The monthly trends of NO_3-N losses for four representative years for wet, dry, and normal weather conditions are shown in figure 7. This figure shows that PM treatment exhibits much lower monthly nitrate losses compared to PM2 and UAN treatments ($p < 0.05$). In addition, in the wet years (1999, 2007, 2008, and 2009), analyses showed that PM treatment produced the lowest NO_3-N losses among all four treatments (including the control treatment, due to the high volume of tile flow that occurred under the control treatment). Similar findings of seasonal effects on NO_3-N losses were observed by other researchers in experiments conducted in the Midwest and other areas (Sharpley and Syers, 1979; Shepherd and Bhogal, 1998; Orecroft et al., 2000; Jaynes and Colvin, 2006; Bakhsh et al., 2010).

Effects of N Treatments on Crop Yield

Average corn and soybean grain yields from all N treatments over the 12 years are presented in table 5. Corn grain yield was higher with PM2 treatments compared with PM and UAN treatments (11.1, 10.1, and 9.7 Mg ha^{-1}, respectively). Poultry manure treatments (both PM2 and PM) resulted in significantly higher soybean yield compared to the UAN treatment overall (3.5 and 3.3 Mg ha^{-1} vs. 2.8 and 2.4 Mg ha^{-1}). On average, the crop yield responded to different N treatments in the order of PM2 > PM = UAN > None for corn, and PM2 > PM > UAN > None for soybean. A crop yield comparison indicated that N application from poultry manure at twice the agronomic recommended rate (336 kg N ha^{-1}) increased corn and soybean yields by only 9% on average compared to the 168 kg N ha^{-1} treatment. PM treatment also resulted in higher soybean yield compared to UAN treatment ($p = 0.048$), although no N application was made to soybeans. This increased soybean yield may reflect the effect of the previous year's treatment application, when the same area was under the corn crop.

The findings from this long-term study show promising results for the use of poultry manure to reduce NO_3-N leaching to tile waters and improve yields when compared to traditional UAN application. Such long-term studies are rare but are needed to assess the impacts of land management practices on water quality and to differentiate these impacts from the year-to-year variation due to weather patterns and hydrology. With the emergence of more corn-on-corn systems due to the push for increased biofuel production, we also recommend the study of annual poultry manure application prior to corn planting with

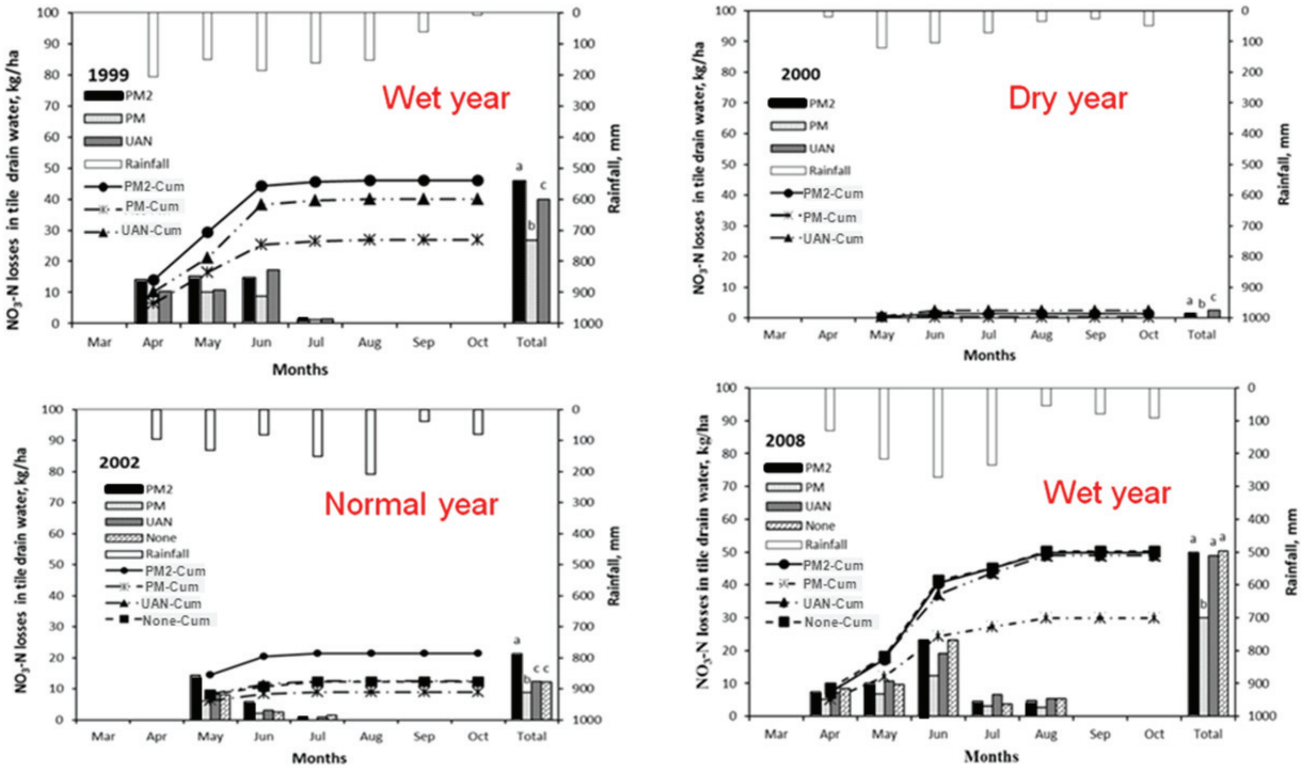

Figure 7. Temporal effects of average (1998-2009) NO_3-N losses in response to rainfall distribution.

Table 5. Annual average crop yields as a function of N treatment.[a]

	Corn Yield (Mg ha^{-1})				Soybean Yield (Mg ha^{-1})			
Year	PM2	PM	UAN	None	PM2	PM	UAN	None
1998	9.8	9.4	8.4	4.1	4.3	3.9	4.0	3.5
1999	10.8	10.9	8.9	5.7	3.8	3.8	3.5	3.4
2000	10.0	9.9	8.9	6.5	3.3	3.3	2.7	2.4
2001	9.4	9.2	8.1	6.2	3.3	3.1	2.7	2.3
2002	11.4	10.6	9.7	4.6	2.1	2.3	1.5	0.7
2003	10.2	9.5	9.0	6.3	3.0	3.1	2.8	2.5
2004	11.2	9.5	10.5	6.0	3.9	3.7	3.4	2.6
2005	12.4	10.4	11.8	6.3	4.2	3.8	2.9	2.3
2006	10.8	9.2	9.7	6.1	3.2	3.2	2.7	2.2
2007	12.7	10.7	11.0	6.8	3.8	3.6	3.0	2.4
2008	12.6	11.0	10.8	4.3	3.1	3.0	2.1	1.8
2009	12.7	10.3	9.8	6.4	3.7	3.1	2.6	2.3
Average[b]	11.1 a	10.1 b	9.7 b	5.8	3.5 a	3.3 b	2.8 c	2.4

[a] Corn yields were corrected to 15.5% moisture content; soybean yields were corrected to 13% moisture content.

[b] Values followed by the same letter are not significantly different at $\alpha = 0.05$. Corn and soybean yield data were analyzed separately.

consideration of the potential for phosphorous build up in the soil. The rich dataset from a corn-on-corn study could be useful in examining in-field nitrogen budgets with poultry manure application, including N_2O emissions, microbial activity, measurements such as denitrification and assimilation, and losses due to unmeasured surface and subsurface transport.

Conclusions

A field study was conducted to investigate the long-term effects of poultry manure application rates and fertilizer formulation on subsurface tile drain water quality under a corn-soybean rotation in Iowa. Nitrogen application treatments included poultry manure at rates of 168 and 336 kg N ha^{-1}, each with three replications, UAN at a rate of 168 kg N ha^{-1} with four replications, and a control treatment (0 kg N ha^{-1}). In each field plot, corn was planted on one half and soybean was planted on the other half. Twelve years of data on tile flow volumes and NO_3-N concentrations in the tile drain water were collected from each plot and analyzed as an unbalanced randomized design with months within year as repeated measures. The objectives of the study were (1) to evaluate the effects of different N application rates (from poultry manure and UAN) on NO_3-N concentrations in tile water and NO_3-N losses with tile drain water, and (2) to compare changes in trends of nitrate losses in tile drain water in response to different N treatments. The following conclusions were made based on the results of this long-term study:

- Field plots receiving poultry manure at an application rate of 168 kg N ha^{-1} resulted in the lowest flow-weighted nitrate concentrations, and lower nitrate losses with tile drain water, compared to UAN application rate of 168 kg N ha^{-1} and poultry N application rate of 336 kg N ha^{-1} at both monthly and yearly levels.
- Long-term application of poultry manure at an N application rate of 168 kg N ha^{-1} resulted in similar crop yields compared to UAN fertilizer at the same N application rate. Increased poultry N application at double the N rate increased crop yields slightly compared to UAN or poultry N application rates of 168 kg N ha^{-1}.
- The patterns of nitrate losses with tile drain water during the growing season were similar for both

poultry manure and UAN treated plots.

- Wet and dry cycles of weather conditions, and the seasonal effects of rainfall distribution during the growing season, resulted in significant effects on the NO_3-N concentration and NO_3-N losses with subsurface drain water.

Current statistics state that approximately 9.5 million ha of Iowa farmland were planted to corn and soybean in 2011, with 5.7 million ha designated to corn. Our study results suggest that poultry manure contains an average N content of 2% at the time of field application, resulting in annual N generation from poultry manure in Iowa of roughly 4.6 million Mg. At a rate of 168 kg N ha^{-1}, less than 3% of Iowa's cropland would be required for utilization of the poultry manure generated each year. Therefore, it can be concluded that land application of poultry manure as a fertilizer may be an environmentally sound option. It should be noted, however, that at the currently accepted application rate of 168 kg N ha^{-1} for both UAN and PM, NO_3-N concentrations measured in tile drainage outflow exceeded the EPA requirements for safe drinking water. Additional research into the fate of N in agricultural systems is needed to address the concerns of NO_3-N losses while meeting the crop nutrient requirements.

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