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Disciplines

Agriculture | Bioresource and Agricultural Engineering | Soil Science | Water Resource Management

Comments

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Effects of liquid swine manure applications on NO_3–N leaching losses to subsurface drainage water from loamy soils in Iowa

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Abstract

Long-term applications of organic or inorganic sources of N to croplands can increase the leaching potential of nitrate–nitrogen (NO_3–N) for soils underlain by subsurface drainage "tile" network. A field study was conducted for 6 years (1993–1998) to determine the effects of liquid swine manure and urea ammonium nitrate (UAN) solution fertilizer applications on NO_3–N concentrations and NO_3–N losses with subsurface drainage water under continuous corn (*Zea maize* L.) and corn after soybean (*Glycine max.* L.) production systems. The field data collected at Iowa State University's northeastern research center near Nashua, Iowa, under six N-management treatments and each replicated three times, were analyzed as a randomized complete block design. The flow weighted average (FWA) NO_3–N concentrations in tile flow were affected significantly ($P < 0.05$) by N-application rates from swine manure, growing season and treatment effects. Peak (FWA) NO_3–N concentrations values of 31.8 mg L^{-1} under swine manure and 15.5 mg L^{-1} under UAN in subsurface drain water were observed in 1995 following the dry year of 1994. The 6-year average crop rotation effects on NO_3–N losses with tile flows were not found to be significantly affected either with swine manure or UAN-fertilizer applications but showed significant increase in corn grain yields under both the systems. Liquid swine manure, averaged across the 6-year period, resulted in significantly ($P < 0.05$) greater NO_3–N losses with tile flows by 53% (26 kg N ha^{-1} versus 17 kg N ha^{-1}) and showed no difference in corn grain yields in comparison with UAN-fertilizer applications under continuous corn production system. These results emphasize the need for better management of swine manure application system during the wet and dry growing seasons to reduce NO_3–N leaching losses to shallow groundwater systems to avoid contamination of drinking water supplies.
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Keywords: Subsurface drainage; Nitrate leaching; Manure; Crop rotation; Loamy soils in Iowa

1. Introduction

Subsurface drainage is necessary to maintain productivity of the poorly drained soils particularly

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in the midwestern parts of the United States where over 30% of the soils are underlain by tile drainage network (Hatfield et al., 1998; Randall, 1998). Subsurface drainage system has been reported intercepting significant amount of nitrate–nitrogen (NO_3–N) losses from the root zone and has been exporting it to the water bodies, which has increased the environmental concerns (Kanwar et al., 1997; Karlen et al., 1998; Bjorneberg et al., 1998; Power and Schepers, 1989). Recently, the expanding zone of hypoxia in the Gulf of Mexico has been associated with increased loading of NO_3–N in the Mississippi River (Rabalais et al., 2002). Many studies have also linked non-point source pollution of water bodies with NO_3–N contamination from agricultural areas and have shown increased NO_3–N concentrations in tile drainage water due to higher application rates of N-fertilizers (Kanwar et al., 1988, 1999; Jaynes et al., 1999; Cambardella et al., 1999). In this context, the role of subsurface drainage system is not fully known for soils where farmers use swine manure as a substitute of commercial, inorganic fertilizer because of its on-farm availability and nutrient value. The fate and transport mechanism of nutrients from manure, however, is more complex than those from inorganic fertilizers and are not well understood (Geohring et al., 1998). Therefore, monitoring of subsurface drainage system can provide useful information to evaluate and improve the effects of farming system on water quality using swine manure or inorganic fertilize (Kanwar et al., 1999; Bakhsh et al., 2001).

Kanwar et al. (1995) reported that different N-application rates from swine manure have affected the NO_3–N concentration in tile flows. Dean and Foran (1992) found that the application of liquid manure to tile drained fields resulted in elevated levels of nutrients and bacteria compared to soils with no manure application. Fleming and Bradshaw (1992) reported maximum levels of 88.2 mg L^{-1} of NH_4–N and 1020 mg L^{-1} total suspended solids. Gupta et al. (1997) reported that disk tillage practice must be preferred over no-till system, if liquid swine manure is to be used as a fertilizer. Edwards and Daniel (1993) found that amounts of constituents lost in runoff were higher for the manure treated plots than those where no manure was applied. Scott et al. (1998) determined that the contaminant discharge from subsurface drains might also have significant water quality impacts to receiving waters. Stoddard et al. (1998) reported that manure significantly increased fecal bacteria in leachate compared with no manure treated plots. These studies, however, have not reported the long-term effects of swine manure application on NO_3–N losses with subsurface drainage water for plots under continuous corn or corn after soybean production system, which is a common farming practice in Iowa.

In Iowa, the number of farms that raise swine has decreased nearly 33% during the past 28 years, from 145,000 in 1970 to 97,000 in 1998, whereas the average size of farmland has increased about 43% over the same period (USDA–NASS, 1999). The number of animals per farm has been reported to increase by 332% from 180 in 1970 to778 in 1996 (Seigley and Quade, 1998). This situation has resulted in the increase of animal waste per farm and ultimately its use over the croplands. Properly used manure can be an excellent natural source of nutrients for crop production. Its improper use, however, can also be a source of pollution to soil and water resources (Bakhsh et al., 1999). The negative effects of swine production on the environment have already led to new legislation that limits the use of animal manure or localization of pig production in some countries (Jongbloed and Lenis, 1998).

Freshly excreted manure has nitrogen in the organic form that is converted to ammonium–nitrogen after application to the soil or during storage. Because ammonium is adsorbed to the soil particles, it generally does not leach from the root zone, but may volatilize as ammonia gas depending on the soil environment and its mode of application. Soil microbes convert ammonium to NO_3, which is highly soluble and can move easily with the soil water. In wet soils, NO_3 may contaminate groundwater through percolation or may be lost as nitrogen gas as a result of denitrification. These N-transformation processes are influenced by environmental and management variables, which determine the potential for NO_3–N contamination (Bakhsh et al., 2000).

Corn–soybean rotation can also affect leaching of NO_3–N because of N-fixation characteristics of soybean. Soybean typically accumulates 25–50% of its N through N-fixation process form atmosphere (Johnson et al., 1975; Harper, 1987) and uses residual and mineralized N for the majority of its N requirement (Olsen et al., 1970). Rotation system can also affect NO_3–N concentrations in the soil profile because soybean does not receive N-fertilizer application. Moreover, low C/N ratio of soybean residue can influence the mineralization processes taking place in the root zone (Katupitiya et al., 1997). Bakhsh et al. (2001) reported that cultural practices needed to be developed to reduce the off-season losses of nitrate from the root zone. They also suggested that using swine manure as nitrogen supplement resulted in greater residual soil nitrate without increasing corn grain yield in comparison to urea ammonium nitrate (UAN)-application and, therefore, could possibly buildup excessive nitrate amounts in the root zone causing increased potential for NO_3–N leaching to groundwater. Based on these studies, the response of corn–soybean rotation system to NO_3–N losses with subsurface drainage water is not clear when swine manure is used to supplement N during its corn phase of production and also due to slow release of N from manure. Therefore, this study was conducted from 1993 to 1998, to determine the effects of swine manure and urea ammonium nitrate solution fertilizer applications on NO_3–N losses with subsurface drainage water under continuous corn and corn after soybean production systems. The specific objectives, however, were: (1) investigate the liquid swine manure and UAN solution fertilizer treatment effects on the FWA NO_3–N concentrations in subsurface drainage water seasonally as well as over the study period from 1993 to 1998; (2) determine the crop rotation effects on the NO_3–N leaching losses in subsurface drainage water and also their effects on the crop yields.

2. Materials and methods

2.1. Experimental design and data analysis

Field experiments were conducted at Iowa State University's Northeastern Research Center near Nashua, IA, on Floyd loam (fine-loamy, mixed, mesic Aquic Hapludolls), Kenyon loam (fine-loamy, mixed, mesic Aquic Hapludoll) and Readlyn loam (fine-loamy, mixed, mesic Aquic Hapludolls) soils (Karlen et al., 1991). The soil particle size distribution for these soils varies from 200 to 280 g kg^{-1} for clay, from 310 to 420 g kg^{-1} for silt and from 380 to 440 g kg^{-1} for sand over the soil profile of 1.2 m depth below the ground surface. These soils contain 30–40 g kg^{-1} (3–4%) organic matter, are moderately well to poorly drained, and have a seasonally high water table (USDA-SCS, 1982). The site also has approximately 60 m of pre-Illinoian till overlying a carbonate aquifer, although in some areas bedrock is near the surface.

The experimental site has 36 plots (each plot is 58.5 m $\times$ 67 m), with fully documented tillage and cropping records for the past 22 years and tile monitoring records for each plot since 1989. From 1978 to 1992, these plots were in a randomized complete block design with four tillage treatments (ridge-tillage, moldboard, chisel and no-till) and cropping systems consisting of either continuous corn or a corn–soybean rotation. In 1993, the study was changed to include only two tillage treatments (chisel or no-till) in order to accommodate N-management treatments with UAN or liquid swine manure. Following the conversion, 18 plots were used to study six management systems: (1) continuous corn fertilized with UAN (CCF); (2) continuous corn with liquid swine manure (CCM); (3) corn after soybean with UAN (CSF); (4) corn after soybean with swine manure (CSM); (5) soybean after corn with UAN applied to corn only (SCF); (6) soybean after corn with swine manure applied to corn only (SCM). Injected UAN provided 135 kg N ha^{-1} to continuous corn or 110 kg N ha^{-1} to corn grown in rotation (Table 1). The 6-year average amount of N from swine manure was 160 kg N ha^{-1} for continuous corn and 136 kg N ha^{-1} for rotated corn (Table 2). Liquid swine manure was injected in the fall and then plots were chisel plowed within a week to mix manure in the top 100–150 mm of soil. Further detail of swine manure application at this site can be found in Bakhsh et al. (2001). The same varieties of corn (Golden Harvest 2343[1]) and soybean (sands of Iowa[1]) were grown in these plots during the 6-year (1993–1998) study. Corn, whether fertilized with UAN or liquid swine manure, was planted in 750 mm rows into a seedbed prepared by fall chiseling and field cultivating in the spring. Soybean was drilled in 200 mm rows directly into corn stover from the previous year. Corn and soybean yield were measured from each plot using a modified commercial combine (Kanwar et al., 1997).

[1] Use of trade names is for reader information and does not imply any endorsement by Iowa State University or USDA-ARS.

Table 1
Schedule of management activities at the study site

Field operations	1993	1994	1995	1996	1997	1998
Manure application	15 November	12 November	17 November	15 November	10 November	15 November
Fertilizer application[a]	14 May	24 April	12 May	3 May	12 May	1 May
Primary tillage (chisel)	20 November	15 November	20 November	17 November	12 November	17 November
Corn planting	17 May	2 May	16 May	21 May	12 May	5 May
Soybean planting	26 May	17 May	22 May	30 May	16 May	18 May
Cultivation (corn plots)	21 July	2 June	14 June	24 June	19 June	4 June
Approximate corn maturity	1 September	2 September	7 September	5 October	30 September	10 September
Corn harvesting	25 October	28 September	22 September	21 October	10 October	22 September
Soybean harvesting	7 October	6 October	11 October	8 October	2 October	1 October

[a] 110 kg N/ha for corn after soybean in rotation plots (CS) and 135 kg N/ha for continuous corn (CC) plots.

2.2. Subsurface drainage system

The subsurface drainage system was installed in 1979 at the Nashua site. Each plot is drained separately and has tile lines installed in the center of the plot at a depth of 1.2 m with a drain spacing of 28.5 m. The cross contamination of each plot was checked by installing the tile lines on the northern and southern borders of the plot and isolating the eastern and western borders with berms (Kanwar et al., 1999). The central tile lines are intercepted at the end of the plots and are connected to individual sumps for measuring drainage effluent and collecting water samples for chemical analysis. The sumps are equipped with a 110 V effluent pump, water flow meter and an orifice tube to collect water samples. Data loggers, connected to water flow meters, record tile flow data continuously as a function of time. Continuous water sampling for NO_3–N analysis was made using an orifice tube located on the discharge pipe of the sump pump. Approximately 0.2% of the water pumped from the sump flowed through a 5 mm diameter polyethylene tube to water sampling bottle located in the collection sump, each time the pump operated. Cumulative subsurface drain flows were monitored and sampling bottles were removed two times per week beginning from mid-March to the beginning of December during the entire study period. A more detailed description of the automated subsurface drainage system installed at the site can be found in Kanwar et al. (1999).

2.3. Water analysis

The water samples collected for NO_3–N analysis were analyzed spectrophotometrically using a Lachat Model AE ion analyzer (Lachat Instruments, Milwaukee, Wis.[1]). The NO_3–N loss (Kg N ha^{-1}) with subsurface drainage water was calculated by multiplying the NO_3–N concentrations (mg L^{-1}) with the drainage effluent (mm) and dividing it by 100 (conversion factor) for each interval of sampling, i.e. two times per week. The cumulative NO_3–N loss and drainage effluent for the entire monitoring season were used to calculate the weighted average NO_3–N concentrations for that year (Bjorneberg et al., 1998).

2.4. Statistical analysis

Subsurface drainage, flow weighted average NO_3–N concentrations in tile flows and seasonal cumulative NO_3–N losses with tile flow data for the six treatments were analyzed using a randomized complete block

Table 2
Actual application rates (kg ha^{-1}) of N, P, K from swine manure applications for 6years (1993–1998)

Application rates	1993		1994		1995		1996		1997		1998		Average	
	CS	CC	CS	CC	CS	CC	CS	CC	CS	CC	CS	CC	CS	CC
N	82	68	236	262	206	260	82	101	85	103	124	164	136	160
P	26	23	77	94	38	64	11	16	12	15	16	21	30	39
K	66	51	156	310	96	119	30	44	37	44	52	65	73	105

CC, continuous corn; CS, corn after soybean.

Table 3
Analysis of variance for tile flow, NO_3–N concentrations and nitrate loss with tile water on a yearly basis

Sources of variability	d.f.	1993	1994	1995	1996	1997	1998
	P-values (tile flow/subsurface drain water)						
Blocks (blk)	2	0.89	0.66	0.68	0.57	0.66	0.92
Cropping systems (trt)	5	0.38	0.37	0.25	0.48	0.16	0.69
Error (blk × trt)	10						
	P-values (NO_3–N concentrations in tile water)						
Blocks (blk)	2	0.19	0.22	<0.01	0.20	0.00	0.29
Cropping systems (trt)	5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Error (blk × trt)	10						
	P-values (NO_3–N loss with tile water)						
Blocks (blk)	2	0.88	0.82	0.83	0.80	0.76	0.85
Cropping systems (trt)	5	0.46	0.15	0.07	0.22	0.19	0.18
Error (blk × trt)	10						

d.f., degree of freedom; $P > F$, probability values.

design. PROC GLM procedure in SAS Version 6.1 (SAS, 1989) was used and analysis of variance (ANOVA) tables were developed. Least significant difference (LSD) values were used to compare treatment means and evaluate the cropping system effects on subsurface drainage, flow weighted average NO_3–N concentrations and NO_3–N losses with subsurface drainage on a yearly basis as well as over the years with data from continuous corn and corn after soybean production systems. The statistical analyses were conducted separately for corn and soybean yield data using PROC GLM procedure as a randomized complete block design.

3. Results and discussion

3.1. Flow weighted average NO_3–N concentrations in subsurface drain water: UAN-fertilized plots

The cropping system effects on FWA NO_3–N concentrations were found to be highly significant ($P < 0.01$) both on individual year basis (Table 3) as well as over the 6-year averages (1993–1998) (Table 4). But treatment effects on subsurface drainage flows and NO_3–N losses with subsurface drainage water were found to be non-significant because drain flows were found to be highly correlated with growing season rainfall ($R^2 = 0.90$), which varied considerably over the years. The 1993 was a wet year with a growing season (March through November) rainfall of about 1030 mm compared to a normal rainfall amount of 840 mm at the research site (USDA-SCS, 1995). During the years of 1994, 1996 and 1997, seasonal rainfall was below normal with total rainfall of 750, 683 and 747 mm, respectively, while during 1995 (802 mm), it was close to normal and in 1998 (979 mm) it was slightly above normal.

The subsurface drain (tile) flow varied from year to year and ranged from 51 mm in 1996 to 361 mm in 1993 (Table 5). Some significant differences in tile flow were observed among treatments for some of the years that had rainfall less than the normal rainfall and

Table 4
Analysis of variance for annual values for tile flow, NO_3–N concentrations and NO_3–N loss with tile water using 6 years (1993–1998) of data

Sources of variability	Tile flow		NO_3–N concentrations[a]	NO_3–N loss with tile flow
	d.f.	*P*-values	*P*-values	*P*-values
Blocks (blk)	2	0.50	<0.01	0.63
Treatments (trt)	5	0.34	<0.01	0.06
Error	10			
Year	5	<0.01	<0.01	<0.01
Year × trt	25	0.16	<0.01	0.02
Error	60			

[a] Flow weighted annual average NO_3–N concentrations in tile flow; d.f., degree of freedom.

Table 5
Treatment means for annual tile flow (mm) on yearly basis

Cropping systems	Years						
	1993	1994	1995	1996	1997	1998	Average (1993–1998)
CCF	392 a	71 a,b	112 a,b	43 a	61 b	185 a	144 a
CCM	389 a	57 a,b	119 a,b	45 a	84 a,b	193 a	148 a
CSF	352 a	29 b	67 b	49 a	50 b	187 a	122 a
CSM	260 a	122 a	71 b	94 a	55 b	313 a	153 a
SCF	283 a	56 a,b	95 a,b	38 a	55 b	206 a	122 a
SCM	488 a	64 a,b	244 a	39 a	206 a	163 a	200 a
Avg.	361	67	118	51	85	207	148
C.V.	36	73	76	74	86	57	53
S.E.	76	28	51	22	42	68	25
$LSD_{(0.05)}$	239	88	162	69	133	215	80

Treatment means followed by letters (a–c) are significantly ($P < 0.05$) different from each other within that duration; CCF, continuous corn with UAN-fertilizer application; CCM, continuous corn with liquid swine manure application; CSF, corn after soybean with UAN-fertilizer application; CSM, corn after soybean with liquid swine manure application; SCF, soybean after corn with UAN-fertilizer application to corn; SCM, soybean after corn with liquid swine manure application to corn; Avg, average; C.V., coefficient of variation in percent; S.E., standard error; $LSD_{(0.05)}$, least significant difference at 5% significance level.

can be attributed to the spatial variability effects which were probably more pronounced during dry years at this site (Bjorneberg et al., 1998). Treatment effects on tile flow were not significant for 1993 and 1998 that had rainfall greater than the normal annual rainfall. The dry years of 1994, 1995 and 1997 showed significant ($P < 0.05$) differences in tile flow for plots treated with manure (Table 5). In 1994, significant difference in tile flow was observed between corn after soybean plots fertilized with manure and UAN (122 mm versus 29 mm). In 1995, soybean plots resulted in higher tile flows in comparison with corn plots with manure application (244 mm versus 71 mm). Similar trends were also observed in 1997 (206 mm versus 55 mm). When averaged over 6-year period, rotated soybean plots with manure application to corn resulted in greater tile flow (200 mm versus 153 mm) compared to corn plots with similar N-management (Table 5). This finding shows that soybean results in higher subsurface drainage and promotes percolation in comparison with corn probably due to its different rooting and water use characteristics (Tan et al., 2002).

The FWA NO_3–N concentrations have been reported to be a better indicator for assessing the overall contamination levels of groundwater (Jaynes et al., 1999; ISU, 1998). The average values of FWA NO_3–N concentrations varied from 9.1 mg L^{-1} in 1997 to 17.9 mg L^{-1} in 1995 (Table 6). The seasonal variation in FWA NO_3–N concentrations can be associated with variable amounts of rainfall over the years. The highest FWA NO_3–N concentrations in 1995 were due to poor growing season as a result of heavy hail damage to the crops (Bjorneberg et al., 1996) reducing the plant N-uptake in 1995 and partially due to previous dry weather of 1994 (Randall, 1998). The combined effects of poor growth of crops in 1995 and 1994 being a dry year resulted in the greatest FWA NO_3–N concentrations for 1995.

Effects of crop rotation, under UAN-applications, on FWA NO_3–N concentrations varied from year to year and were not found to be significant when averaged over 6-year period (Table 6). Rotation effect (continuous corn versus corn after soybean) on FWA NO_3–N concentrations was found to be significant in 1993, 1996 and in 1997. Crop rotation system under UAN-applications, however, showed interesting results among the corn soybean system. For the first 2 years of study, period in 1993 and 1994, continuous corn showed higher FWA NO_3–N concentrations in tile water and then corn after soybean resulted in greater FWA NO_3–N concentrations in tile water for 1995, 1996 and 1997 (Table 6). In 1998, all three treatments with UAN-applications did not show any significant difference in FWA NO_3–N concentrations in tile water. This shows that after excessive flushing of NO_3–N from the soil profile in 1993, the residual soil nitrate had started to build up (Bakhsh et al.,

Table 6
Treatment means for annual flow weighted average NO_3–N concentrations (mg L^{-1}) in tile flow

Cropping systems	Years						
	1993	1994	1995	1996	1997	1998	Average (1993–1998)
CCF	12.2 a	11.0 b	14.3 d	7.8 c	7.2 b	12.8 b,c	11 c
CCM	12.4 a	16.7 a	31.8 a	24.3 a	7.6 b	21.1 a	19 a
CSF	9.3 b	9.3 b,c	15.5 c,d	13.0 b	12.4 a	12.7 b,c	12 c
CSM	12.9 a	11.0 b	18.2 b	15.6 b	13.0 a	14.5 b	14 b
SCF	11.5 a,b	6.2 c	10.9 e	15.1 b	6.8 b	11.9 b,c	10 c
SCM	6.7 c	7.3 b,c	16.7 b,c	20.2 a	7.5 b	11.2 c	12 c
Avg.	10.8	10.3	17.9	16.0	9.1	14.0	13.0
C.V.	13	24	7	15	12	13	13
S.E.	1	1	1	1	1	1	0.4
$LSD_{(0.05)}$	2.5	4.5	2.2	4.3	2.0	3.2	1.7

Treatment means followed by letters (a–c) are significantly ($P < 0.05$) different from each other within that duration; CCF, continuous corn with UAN-fertilizer application; CCM, continuous corn with liquid swine manure application; CSF, corn after soybean with UAN-fertilizer application; CSM, corn after soybean with liquid swine manure application; SCF, soybean after corn with UAN-fertilizer application to corn; SCM, soybean after corn with liquid swine manure application to corn; Avg., average; C.V., coefficient of variation in percent; S.E., standard error; $LSD_{(0.05)}$, least significant difference at 5% significance level.

2001), which possibly increased the FWA NO_3–N concentrations under corn–soybean rotation in comparison with continuous corn system in 1995, 1996 and 1997 (Harper, 1987). Despite the fact that corn after soybean plots always received N-application of 110 kg N ha^{-1} during its corn phase of production in comparison to receiving 135 kg N ha^{-1} every year for continuous corn. This shows that N-fixation characteristic of soybean should have contributed to N-pool in the soil and corn–soybean rotation plots resulted in as much or even higher FWA NO_3–N concentrations in tile water in comparison with continuous corn plots. This fact became more apparent in 1996 when crop uptake was relatively less in 1995 due to heavy hail damage of crops. Similar findings have been reported by David et al. (1997) and Gentry et al. (1998). The analysis of data on NO_3–N concentrations in tile water further revealed that, in addition to N-management effects, the levels of FWA NO_3–N concentrations were affected by the rainfall pattern in wet and dry years.

3.2. Manure treated plots

The FWA NO_3–N concentrations from plots receiving liquid swine manure applications varied from year to year. Rainfall patterns and variable N-application rates from liquid swine manure affected the FWA NO_3–N concentrations as well. The analysis of variance showed a highly significant effect ($P < 0.01$) of season and its interaction with the treatments on FWA NO_3–N concentrations (Tables 3 and 4). The highest N-application rates from swine manure were made in 1994 and 1995 because of the variability in the quality of liquid swine manure in terms of solid concentrations and the available form of ammonium–nitrogen and NO_3–N levels at the time of application (Bakhsh et al., 2001). The effect of large N-application rate on FWA NO_3–N concentrations appeared in 1995 that raised FWA NO_3–N concentration to the level of 31.8 mg L^{-1} (Table 6). The continuous corn plots showed higher FWA NO_3–N concentrations in 1996 even when the N-application rate from manure was much lower (101 kg N ha^{-1}) in 1996. This might be the result of slow release of N associated with soil N-pool from previous year (Gentry et al., 1998; Cambardella et al., 1999). In 1997, rotational corn plots showed significantly ($P < 0.05$) higher FWA NO_3–N concentrations in comparison with the continuous corn plots (Table 6). This difference can be attributed to the release of fixed N from decay of soybean roots from previous years. The significant differences in FWA NO_3–N concentrations between treatments in 1998 could be due to different N-application rates. Subsurface drainage system, however, showed immediate response to higher N-application rates in 1998, which could be due to buildup of N-pool from manure applications during the previous years. Rotation effect on FWA NO_3–N concentrations with liquid swine manure was found to be significant ($P < 0.05$), when averaged over the 6-year data. Continuous corn plots resulted in significantly ($P < 0.05$) higher FWA NO_3–N concentrations than corn after soybean system (19 mg L^{-1} versus 14 mg L^{-1}). Similarly corn after soybean showed significantly higher FWA NO_3–N concentrations than soybean after corn (14 mg L^{-1} versus 12 mg L^{-1}) (Table 6).

The trend in the FWA NO_3–N concentrations under liquid swine manure and UAN-fertilizer applications was found to be similar over the 6-year period, but NO_3–N concentrations under UAN-applications were significantly lower from 1994 to 1996. The peak values of FWA NO_3–N concentrations for both the N-sources (31.8 mg L^{-1} under manure and 14.3 mg L^{-1} under UAN) were highest in 1995 (Table 6) for the continuous corn production system. The manure treated plots under continuous corn always resulted in higher FWA NO_3–N concentrations in comparison with corn after soybean production systems. The results of this analysis show that N-application rates and the amount of rainfall during the growing season were the major factors affecting NO_3–N concentrations in subsurface drain water. A drier 1994-year and poor growing season conditions in 1995 resulted in increased FWA NO_3–N concentrations in 1995 (Table 6).

3.3. NO_3–N losses with tile flows

NO_3–N losses with tile flow were affected significantly by the volume of tile flow because of high correlation ($R^2 = 0.90$) between annual tile flows and annual NO_3–N losses. The effect of cropping system on NO_3–N losses with tile flows was not found to be significant ($P < 0.05$) either on yearly basis (Table 3) or on cumulative basis for 6 years (Table 4). Seasonal interactions when combined with treatment effects affected significantly the NO_3–N losses with tile flows (Table 4). The average annual NO_3–N losses with tile flow varied from 7 kg N ha^{-1} in 1994 and 1997 to 38 kg N ha^{-1} in 1993 (Table 7) primarily because of variability in rainfall amounts over the years. In 1993, although maximum amount of NO_3–N losses occurred but differences among treatments were insignificant (Table 7). Similarly dry years of 1994 and 1996 resulted in lower NO_3–N losses with tile flows indicating a direct relationship between NO_3–N loss and tile flow amounts. The variability in NO_3–N leaching losses in subsurface drainage water over the years can also be explained using corn grain yield data because of the associated plant N-uptake effects on NO_3–N leaching losses (Table 8). Greater NO_3–N leaching losses resulted in lower corn grain yield in respective years except 1998 that showed higher NO_3–N leaching losses as well as greater corn grain yield (Table 8) due to its climatic effects.

Table 7
Treatment means for annual nitrate loss with tile flow (kg N ha^{-1})

Cropping systems	Years						
	1993	1994	1995	1996	1997	1998	Average (1993–1998)
CCF	47 a	8 a,b	16 a,b	4 b	4 b	23 a,b	17 b
CCM	48 a	10 a,b	38 a	11 a,b	7 a,b	41 a	26 a
CSF	33 a	3 b	10 b	6 a,b	6 a,b	24 a,b	14 b
CSM	35 a	12 a	13 b	13 a	8 a,b	40 a,b	20 a,b
SCF	32 a	3 b	10 b	6 a,b	4 b	25 a,b	13 b
SCM	33 a	4 a,b	39 a	8 a,b	15 a	19 b	20 a,b
Avg.	38	7	21	8	7	28	18
C.V.	33	66	65	57	74	42	47
S.E.	7	3	8	3	1	7	2
$LSD_{(0.05)}$	23	8	25	8	10	21	8

Treatment means with different letters (a–c) are significantly ($P < 0.05$) different from each other within that duration; CCF, continuous corn with UAN-fertilizer application; CCM, continuous corn with liquid swine manure application; CSF, corn after soybean with UAN-fertilizer application; CSM, corn after soybean with liquid swine manure application; SCF, soybean after corn with UAN-fertilizer application to corn; SCM, soybean after corn with liquid swine manure application to corn; Avg., average; C.V., coefficient of variation in percent; S.E., standard error; $LSD_{(0.05)}$, least significant difference at 5% significance level.

Table 8
Treatment means for crop yield (mg ha^{-1})

Treatments	Years						
	1993	1994	1995	1996	1997	1998	Average (1993–1998)
Corn							
CCF	4.6 b	5.8 c	4.6 c	7.0 c	8.6 b	7.8 b	6.4 b
CCM	3.1 c	7.4 b	5.4 b,c	7.9 b	7.6 c	7.2 c	6.4 b
CSF	5.1 b	7.9 a,b	6.0 a,b	8.8 a	9.8 a	9.7 a	7.9 a
CSM	6.3 a	8.4 a	6.5 a	8.6 a	8.8 b	9.6 a	8.0 a
Avg.	4.8	7.4	5.6	8.1	8.7	8.6	7.1
C.V.	7.7	4.8	9.5	3.3	4.8	2.6	6.7
S.E.	0.2	0.2	0.3	0.2	0.2	0.1	0.1
LSD	0.7	0.7	1.0	0.5	0.8	0.4	0.2
Soybean							
SCF	2.6 a	3.6 a	3.3 a	4.1 a	3.6 a	4.0 a	3.6 a
SCM	2.6 a	3.3 b	3.3 a	3.9 a	3.7 a	3.9 a	3.4 b
Avg.	2.6	3.4	3.3	4.0	3.7	3.9	3.5
C.V.	1.1	1.2	2.5	2.1	1.4	5.3	3.3
S.E.	0.02	0.02	0.05	0.05	0.03	0.1	0.03
LSD	0.1	0.1	0.3	0.3	0.2	0.7	0.05

Treatment means followed by letters a–c are significantly ($P < 0.05$) different from each other within that duration; CCF, continuous corn with UAN-fertilizer application; CCM, continuous corn with liquid swine manure application; CSF, corn after soybean with UAN-fertilizer application; CSM, corn after soybean with liquid swine manure application; SCF, soybean after corn with UAN-fertilizer application to corn; SCM, soybean after corn with liquid swine manure application to corn; Avg., average; C.V., coefficient of variation in percent; S.E., standard error; $LSD_{(0.05)}$, least significant difference at 5% significance level.

When averaged over 6-year from 1993 to 1998, the manure treatments under continuous corn resulted in significantly ($P < 0.05$) greater NO_3–N losses with tile flows by as much as 53% (26 kg N ha^{-1} versus 17 kg N ha^{-1}) compared to UAN-fertilized plots (Table 7). The crop rotation effects on NO_3–N losses with tile flow were not found to be significant either under UAN-fertilized or manure treated plots. When averaged across 6-year period (1993–1998), plots under corn after soybean resulted in about similar amounts of NO_3–N losses as were observed from soybean plots after corn either fertilized with manure (20 kg N ha^{-1} versus 20 kg N ha^{-1}) or UAN (14 kg N ha^{-1} versus 13 kg N ha^{-1}) (Table 7). These results suggest the possibility of build up of N pools, which continue to remineralize in the subsequent years (Cambardella et al., 1999; Gentry et al., 1998). The leaching losses of NO_3–N with tile flows appear to be affected by complex interaction between climate, i.e. cycle of dry and wet years, N-application rates and the growing conditions. Assessment of proper N credit to soybean and the storage of mineralizable N in the root zone may be needed before N-applications either form organic or inorganic sources in order to reduce the leaching potential of NO_3–N with tile flows.

4. Conclusions

Liquid swine manure can be a good source of plant nutrients (N, P, K) but excessive applications of manure can result in groundwater contamination. Six years of field study on determining the effects of liquid swine manure on NO_3–N losses with subsurface drain flow resulted in the followings:

(1) Manure applications resulted in significantly ($P < 0.05$) greater flow weighted average NO_3–N concentrations in tile water (31.8 mg L^{-1} under liquid swine manure and 15.5 mg L^{-1} under UAN-applications in 1995). The NO_3–N concentrations in tile water were significantly affected by the seasonal rainfall and differences in crop growing conditions.
(2) Applications of liquid swine manure, when averaged over 6-year period, resulted in significantly

($P < 0.05$) greater NO_3–N losses with tile flows in comparison with UAN-applications (26 kg N ha^{-1} versus 17 kg N ha^{-1}) under continuous corn production system but no differences were observed in corn grain yields.

(3) The crop rotation effects, when averaged over 6-year period, showed no significant difference in NO_3–N leaching losses but increased corn grain yield significantly ($P < 0.05$) under swine manure and UAN-fertilizer applications. This shows that corn–soybean production system is a better system to manage swine manure applications for water quality and crop production benefits.

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