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Swine Manure Rate, Timing, and Application Method Effects on Post-Harvest Soil Nutrients, Crop Yield, and Water Quality Implications in a Corn-Soybean Rotation

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Abstract. *This report documents results from a six-year study (1996-2001) that evaluated effects of liquid swine manure application management practices on soil nutrients, organic matter, pH, crop yield; and also discussed water quality implications. Swine manure management practices included single-rate (SR) and double-rate (DR) nitrogen (N)-based application rates (168 and 336 kg N ha^{-1}, respectively), three timings (fall injection [FI], winter broadcast [WB], and spring injection [SI]), and two methods (broadcast and injection) of liquid swine manure. Analysis of these practices involved comparing levels of residual soil total phosphorus (P) as Bray-1 available P (RSP), residual soil nitrate-N (RSN), percent organic matter (OM%), pH, carbon:nitrogen (C:N) ratio, and crop yields (kg ha^{-1}) in a corn-soybean rotation. Results of this study indicated that long-term application of higher liquid swine manure rates during winter and spring application times resulted in significantly higher post-harvest accumulation of RSN and RSP in the soil profile, with no significant changes in soil OM%, pH, and C:N ratio. These results also showed that incorporation of swine manure during the spring application time produced significantly higher corn yields compared with fall and winter application times. Overall results suggest that while RSN and RSP content may be significantly higher from spring versus fall manure application times, N and P runoff losses and the potential threat to surface water quality may be substantially lower during spring and summer compared with fall and winter due to effects from crop nutrient uptake, microbial activity, leaching, and evapotranspiration during the growing season.*

Keywords. *Best management practices, Corn-soybean rotation, Cover crops, Manure application, Nitrogen, Phosphorus, Soil nutrient content, Water quality implications*

The animal production industry in Iowa has posed a serious threat to the state's surface and groundwater quality (USDA-IFB, 1998), and nonpoint source (NPS) pollution from agricultural nutrients continues to be recognized as a significant contributor to poor water quality throughout much of the United States (USEPA, 2009; USGS, 2010). Iowa is the number one pork producer in the United States (USDA-NASS, 2011); generating a large volume of swine manure and prompting a need for new manure management strategies. These strategies include improved storage and handling of manure for minimizing off-site impacts of manure management. One step towards a more sustainable approach to enhancing soil and water quality is through the efficient use of livestock manure on cropland and pasture areas.

Swine, cattle, and poultry manures are valuable resources as fertilizers and soil amendments. However, several studies have documented that manure and inorganic fertilizer applications are significant sources of excessive soil nitrogen (N) and phosphorus (P), resulting in increased leaching of nitrate-N (NO_3-N) and runoff losses of P if not properly managed (Sims, 1987; Roth and Fox, 1990; Gilley et al., 2002; Daverede et al., 2004; Gessel et al., 2004; Bakhsh et al., 2005; Ball Coelho et al., 2007; Allen and Mallarino, 2008; Wienhold and Gilley, 2010) and can lead to hypoxic conditions in the Gulf of Mexico (David et al., 2010; Jacobson et al., 2011). Khaleel et al. (1980) determined that field plots receiving manure during winter and spring followed a different relationship compared to plots receiving applications during spring and summer, with snowmelt runoff contributing up to two to three times more nutrients versus rainfall-runoff. Another study by van Es et al. (2006) found that significant N-leaching was preceded by dry growing seasons where high residual N levels contributed to high leaching concentrations.

Kanwar et al. (1996) reported that swine manure and other N-management systems can be successfully used to reduce leaching of NO_3-N to shallow ground water without sacrificing crop yields, and Ferguson et al. (2005) found that repeated annual manure applications resulted in acceptable soil profile NO_3-N concentrations over the short term. Several studies also have shown that the following livestock manure management strategies and conditions may reduce water pollution and include rate, method, and timing of manure application; soil type, tillage practices, crop rotation, rainfall conditions, and livestock feeding rations (Boddy and Baker, 1990; Ahmed and Kanwar, 1997; Xue et al., 1999; Bakhsh et al., 2000; Pote et al., 2001; Kleinman and Sharpley, 2003; Zhu and Fox, 2003; Allen and Mallarino, 2006; van Es et al., 2006; Gilley et al., 2007; Shigaki et al., 2007; Wu and Powell, 2007; Pappas et al., 2008; Powell and Grabber, 2009).

Rate, method, and timing of application of organic and inorganic fertilizers also affect concentration of residual soil-N (RSN) in the soil profile and movement to shallow groundwater (Gast et al., 1978; Kanwar et al., 1985; Jokela, 1992). Randall et al. (1997) reported that late-season N applications resulted in highest RSN compared to spring application in the top 0-1.0 m of the soil profile. Gilley et al. (2007) found that tillage appeared to have less of an impact on runoff nutrient transport from cropland areas than length of time since manure application. Qian and Schoenau (2000) also found that manure applications significantly increased N and P supply rates in soil not otherwise fertilized. Some other studies in North America showed that soil nutrient accumulation in the soil profile was related to soil texture (Eghball et al., 1996) and high water tables (Simard et al., 1995). Mallarino and Wittry (2010) studied the effects of fixed and variable rates of liquid swine manure on crop yield and soil P within a corn (*Zea mays* Linnaeus)-soybean (*Glycine max* L.) cropping system. They reported that manure rates did not significantly affect crop yield; however, variable rate manure application reduced P accumulation in the soil profile.

Schoenau et al. (1999) reported that manure application rates higher than the crop's nutrient demands resulted in post-harvest accumulation of nutrients in the soil profile and posed an environmental concern. Vadas et al. (2007) also determined that management practices for water quality must consider the potential for manure P transformations to contribute dissolved P to runoff long after manure is applied. A six-year swine manure application study by Novak et al. (2000) showed that accumulation and additional leaching of residual soil P (RSP) in plots where manure was applied were not significantly different than the control plots. Kleinman et al. (2002) determined that mixing mineral and manure P sources into the soil significantly decreased P losses relative to surface P application. Although Gangbazo et al. (1997) found that swine manure applications were no greater threat to the environment than mineral fertilizers; Barbazan et al. (2009) found no evidence supporting a reduction in crop-P availability from liquid swine manure versus fertilizer-P applications. However, other more recent studies tend to support the assertion that manures are more environmentally sustainable than inorganic fertilizers (Sharpley et al., 2001; Tabbara, 2003; Loecke et al., 2004; Smith et al., 2007). Nayak et al. (2009) conducted a six-year field study to investigate the effects of swine manure application on P accumulation in the soil profile and found nutrients from inorganic fertilizer are more susceptible to leaching to tile drains than nutrients from manure; however, P from manure was determined to increase in the surface soil by two to six times higher than the agronomic optimum range.

Patni et al. (1999) found a low potential of NO_3-N leaching in manured plots and Ball Coelho et al. (2007) reported that injected liquid swine manure supplied adequate crop nutrients without compromising drainage water quality. Jokela (1992) documented that there was very little difference in RSN between manure and N-fertilizer applied plots and Kwaw-Mensah and Al-Kaisi (2006) reported that liquid swine manure N-source should be considered a strong alternative to commercial N-fertilizer depending on its availability and logistics of application. Meng et al. (2005) also determined that manure added to a soil did not result in greater N_2O emissions than a treatment with an N-containing fertilizer, but did confer greater benefits for soil fertility and the environment. Following a comprehensive literature review of manure management technologies in no-till and forage systems, Maguire et al. (2011) reported that while improvements have been made to manure land application and farming system sustainability with alternatives to surface broadcasting, many questions remain concerning which technologies work best for particular soils, manure types, and farming and cropping systems.

Continuous application of manure to agricultural lands also can affect other soil characteristics. Soil organic matter (OM) has long been recognized as a key element in soil quality (Reeves, 1997); which helps maintain soil in an uncompacted condition with a lower bulk density, improving air and water movement and storage in soil. Haynes and Naidu (1998) reported that the addition of organic manures resulted in increased soil OM, porosity, water holding capacity, and hydraulic conductivity. Slevinskey and Small (1997) investigated physical and chemical changes in a clay soil after repeated applications of swine manure and reported higher electrical conductivity and OM, and lower pH in manured soils than those of non-manured soils. Kingery et al. (1994) found that application of poultry manure increased organic carbon (C) and total-N to depths of 0.15 and 0.30 m, respectively. However, Whalen and Chang (2002) determined that long-term manure applications reduced OM aggregate size and increased C, N, and P concentrations; possibly increasing the risk of soil and nutrient losses through wind erosion.

Many researchers have studied the effect of manure application on crop yield. Mathers and Stewart (1974) determined that sorghum (*Sorghum bicolor* L.) yield was reduced by high rates of manure applications. Another study found that corn yield was decreased when high rates of liquid and solid dairy manure were applied (Sutton et al., 1986). Daliparthy et al. (1995) evaluated the effect of dairy manure on alfalfa (*Medicago sativa* L.) yield and found no adverse effect or economic risk. Jokela (1992) reported that corn yield and N uptake were increased by both N-fertilizer and manure applications. A study by Schmidt et al. (2001) reported an average soybean yield increase with an increase in manure application rate. Spring application of manure increased corn yield by 5% when compared with fall application yield results (Randall et al., 1999). However, Loecke et al. (2004) found that fall application of manure increased corn grain yield more than spring application, with spring application providing no yield response beyond the unamended control.

Some alternative N-management practices include the use of a legume in a crop rotation and a grass species in a cover crop planting, and several studies have shown the economical and environmental benefits of a corn-soybean rotation when compared to continuous corn (Bundy et al., 1993; Karlen et al., 1994; Katupitiya et al., 1997). Corn after soybean or alfalfa typically requires less N-fertilizer than continuous corn to attain optimum yields (Fox and Piekielek, 1988). Increased crop yields also resulted in increased removal of available N in the soil (Lory et al., 1995). Parkin et al. (2006) reported that the use of a rye (Secale cereale L.) cover crop reduced N-load in drainage water when manure was applied to soils. Kovar et al. (2011) determined that liquid swine manure applied with a low-disturbance injection system (in a corn-soybean rotation with a winter wheat/oat cover crop) increased P uptake (due to reduced cover crop damage), increased crop-P availability, and reduced P losses in surface runoff. Rotz et al. (2011) also determined that shallow disk injection of liquid dairy cow and swine manures into corn and grass/alfalfa crop systems provided the greatest environmental benefit at the least cost (and greatest profit) for the producer. Other studies showed the benefits of a corn-soybean rotation in reducing NO_3-N leaching and losses in surface and subsurface drainage (Randall et al., 2003; Zhu and Fox, 2003; Randall and Vetsch, 2005).

Improved manure management for maximizing crop production and minimizing environmental pollution may be achieved by conducting intensive long-term research. Efficient manure management depends on many environmental, biological, and storage handling conditions; and manure application should be evaluated within the limitations of the livestock industry and other local conditions. Consequently, the primary objective of this central Iowa field study was to determine the long-term effects of liquid swine manure application rate, timing, and method on residual soil total P (TP), NO_3-N, percent OM (OM%), and crop yield in a corn-soybean rotation.

Materials and Methods

This study was conducted at the Iowa State University (ISU) Agronomy and Agricultural Engineering Research Center 8 km (5 mi) west of Ames, Iowa USA (42.020 N, 93.780 W). Soils at the research site are predominantly Nicollet, a fine loamy, mixed, mesic Aquic Hapludolls in the Clarion-Nicollet-Webster Soil Association (Andrews and Dideriksen, 1981). The soils are classified as moderately permeable and somewhat poorly drained with selected soil physical properties given in table 1. Table 2 shows experimental sources of variation that include

N-management treatments and application practices conducted at the research site during the study period (1996-2001).

Table 1. Selected soil physical properties at the Iowa State University Agronomy and Agricultural Engineering Research Center site (Kanwar et al., 1988; Blanchet, 1996). Percent organic matter, bulk density, and hydraulic conductivity denoted as OM, BD, and K, respectively.

Soil Depth (m)	Clay %	Silt %	Sand %	OM %	BD gm cm^{-3}	Porosity %	K cm day^{-1}
0-0.15	22.8	35.2	42.0	4.0	1.48	44	3.5
0.15-0.30	27.6	38.2	35.7	4.0	1.35	49	3.5
0.30-0.45	27.5	38.4	34.1	3.2	1.30	51	3.0
0.45-0.91	26.0	36.0	38.0	2.6	1.35	49	2.5
0.91-1.22	21.7	25.2	53.1	0.5	1.43	46	2.0

Table 2. Nitrogen (N)-management treatment and application practice sources of variation conducted at the study site.

Treatment	Application Rate (kg N ha^{-1})	Application Timing	Application Method
Spring UAN (UAN [control])	168	Spring	Broadcast [a]
Fall 1X (FI1)	168	Fall	Inject
Fall 2X (FI2)	336	Fall	Inject
Winter 1X (WB1)	168	Late Winter	Broadcast
Winter 2X (WB2)	336	Late Winter	Broadcast
Spring 1X (SI1)	168	Spring	Inject
Spring 2X (SI2)	336	Spring	Inject

[a] with field cultivator

A randomized block design was used with three replications of seven treatments. Each plot was 7.6 m (25 ft)-wide × 22.9 m (75 ft)-long to accommodate an annual rotation of five-76 cm (30 in.) rows of corn in one-half of the plot and five rows of soybean in the other half. All field work was conducted over the length of the plot, up and down the slope. A 3.7 m (12 ft)-wide field cultivator was used for spring pre-plant tillage. Crops were planted with a five-row modified John Deere 7000 planter. Metalochlor herbicide was applied at the rate of 2.2 kg ha^{-1} (2.0 lb ac^{-1}) and row cultivation was used for additional weed control on all plots. All plots were outfitted with subsurface drainage and surface runoff collection systems and are described in Warnemuende et al. (2001). The subsurface drainage collection system included a 7.6 cm (3.0 in.)-diameter tile drain placed 1.2 m (4.0 ft) deep through the center of each plot. The surface runoff collection system included earthen berms surrounding each plot to protect against cross-contamination due to surface runoff from adjacent plots.

Fall application of liquid swine manure was included as a treatment because it is a common practice in this area due in part to storage issues and ease of application after crop harvest. Table 2 shows the six treatments used to evaluate effects of manure application timing (spring, late fall, and late winter), rate (168 and 336 kg N ha^{-1} [150 and 300 lb N ac^{-1}]), and method (broadcast and inject) on RSP, RSN, OM%, and yields of the rotated corn and soybean crops. These crop available-N rates are standard levels applied to corn and were adjusted for application losses. A control treatment was included in the plots which received 168 kg N ha^{-1} as 28% urea ammonium nitrate (UAN) solution. Manure was injected in the fall using a four-row applicator with 46 cm (18 in.)-wide sweeps at a depth of 15 to 20 cm (6 to 8 in.) and was surface broadcast onto frozen soil in late winter. Manure also was injected by using the same application method in spring. The manure application rates were 168 kg N ha^{-1} as a single rate (SR) and 336 kg N ha^{-1} as a double rate (DR) for all six years of the study.

The manure in this study was obtained from the Iowa State University Swine Nutrition Farm, a finishing facility near Ames, Iowa, and the Iowa State University Swine Breeding Farm near Madrid, Iowa. Manure samples were analyzed for nutrient content by the Iowa Testing Laboratories, Eagle Grove, Iowa, to calculate manure application rates for the experimental treatments (table 3) and are averaged over the six-year study period.

Table 3. Liquid swine manure slurry analysis average data (1996-2001).

Year	Volume L/plot	Volume L/ac	N kg/plot	N kg/ha	P_2O5 kg/plot	P_2O5 kg/ha	K_2O kg/plot	K_2O kg/ha
1996	887	16,672	2.85	54	0.97	18	0.95	18
1997	766	15,219	3.11	58	0.50	9.0	2.42	45
1998	858	14,599	3.09	58	1.44	26	2.00	38
1999	601	12,909	2.69	51	1.61	29	1.39	26
2000	729	10,933	2.31	43	1.28	21	1.78	32
2001	448	11,006	2.65	50	1.71	31	1.33	25

Soil Sampling

Soil samples were collected on August 23, 1996 (prior to all manure and UAN applications) to determine P, N, potassium (K), pH, and OM% in the soil profile (table 4). To determine the impact of liquid swine manure applications on soil nutrients, two different sets of soil cores (0-0.30 and 0-1.22 m-deep) were collected after harvest for every year during the six-year study (1996-2001).

In the first set of soil cores, soil samples were collected annually in late fall (post-harvest). Subsamples for this first set of soil cores were collected from five different locations in each plot for all six years (1996-2001) of the study. The second set of soil cores was collected from the top 0-1.22 m of the soil profile from the third (middle) row of both corn and soybean halves of the plots, and 7.6 m (25 ft) from the bottom edge, after harvest from 1996 to 2001. A hand sampler was used to collect the 0.30 m (12.0 in.)-long × 22.2 mm (9.0 in.)-diameter soil cores. A zero contamination power sampler was used to collect the 1.22 m (48 in.)-long × 38.1 mm (15 in.)-diameter soil cores. As the sampler was pushed into the soil, the soil core entered a liner made of polyethylene terephthalate glycol-modified (PETG) plastic. All soil samples were frozen immediately after collection.

The 0-0.30 m soil samples were cut in half for soil depths of 0-0.15 and 0.15-0.30 m. Five cores for each depth were combined into one composite soil sample for each plot. All 0-0.30 m depth soil samples were analyzed for TP, NO_3-N, OM%, and pH in the soil profile. The 1.22 m soil cores were fractioned into five depth increments of 0-0.15, 0.15-0.30, 0.30-0.61, 0.61-0.91, and 0.91-1.22 m. All soil samples were wrapped in labeled plastic-lined bags and kept frozen until laboratory analysis. The soil cores (0-1.22 m) collected in 1996 and 2000 were analyzed for RSN in the soil profile. The soil cores (0-1.22 m) of 1997, 1998, and 1999 were analyzed for carbon:nitrogen (C:N) ratio at selected depths for the corn plots. The soil samples were analyzed at Iowa State University's Soil Testing Laboratory, Ames, Iowa and the USDA National Laboratory for Agriculture and the Environment, Ames, Iowa.

Table 4. Initial soil sampling average data (sampling date: August 23, 1996; prior to all manure/UAN applications).

Crop	Core depth cm	P ppm	N ppm	K ppm	Soil pH	Buffer pH	OM %
Corn	0-15	21	5	115	6.64	6.84	3.0
Corn	15-30	7	2	114	6.33	6.72	2.7
Soybean	0-15	15	4	113	6.72	6.90	2.9
Soybean	15-30	6	2	108	6.38	6.74	2.6

Chemical Analysis

Soil was analyzed for TP using the ascorbic acid method and Bray and Kurtz P-1 procedure (Bray and Kurtz, 1945) and TP content was determined by mixing dilute ammonium fluoride with 250 mL of 1.0 M HCl. A 1:10 soil-to-solution ratio mixture was shaken at approximately 200 excursions per minute for five minutes at 24 ^{0}C to 27 ^{0}C. Extracts were filtered through Whatman No. 42 filter paper and 2 mL of aliquot extract were added with 8 mL of working solution for mixing and color development. Measurements were made with a colorimeter at a wavelength of 882 nm. Concentrations of TP in samples were determined from intensity and standard curves by using the concentrations in soil extracts (Black, 1965).

The compounds Nitrate-N (NO_3-N) + Nitrite-N (NO_2-N) were analyzed by the automated flow injection Cadmium Reduction method using a Lachat Quickchem 2000 Automated Ion Analyzer system according to Standard Methods (1998). Nitrate-N was reduced to NO_2-N by a cadmium/copper column. Nitrite-N was diazotized with sulfanilamide and then reacted with N-(1-naphthyl-)-ethylenediamine dihydrochloride at a pH of 8.5 to form a colored (pink to red) azo compound in an intensity proportional to the amount of NO_3-N + NO_2-N in the sample. Measurements were made with a colorimeter at a wavelength of 520 nm. Concentrations of NO_3-N and NO_2-N in the samples were determined by comparing sample absorbance with absorbance values obtained from a calibration curve comprised of standards containing NO_3-N concentrations of 0.25 to 20.0 mg N L^{-1}.

Organic matter (OM) was analyzed as percent OM (OM%) using the Walkley-Black method (Walkley and Black, 1934). Soil sample OM% was calculated by assuming 77% oxidation of organic C and that OM% was 58% C (OM% = %C x 1.72). Soil pH was determined using the modified Dumas method (Thomas, 1996). Nitrate-N and TP concentrations were reported in ppm. The concentrations of nutrients were changed to kg ha^{-1} for that soil horizon by multiplying bulk density of soil (g cm^{-3}) by soil depth increment (m) and correcting for appropriate unit conversions. Corn and soybean yield data (kg ha^{-1}) collected from each plot were tested for moisture content and adjusted to a constant water content of 150 g kg^{-1} (15%) for corn and 130 g kg^{-1} (13.0%) for soybean.

The significance among treatments was determined using the General Linear Model (GLM) Procedure at the 1% and 5% probability levels ($p \leq 0.01$ and $p \leq 0.05$, respectively) with Statistical Analysis System (SAS) software version 8.2 (SAS, 1985). Fisher's Least Significant Difference (LSD) Test, Standard Error of the Mean (Stderr), and Contrast Method also were used to statistically analyze differences among the N-management treatments.

Results and Discussion

The total rainfall amounts for the six-year study period (1996-2001) are given in table 5. The average annual rainfall for the study area is 824 mm (32.4 in.), with approximately 550 mm (21.7 in.) occurring during the spring and summer months (NOAA, 1996-2001). The amount of annual rainfall varied during the study period from 461 to 963 mm (18.1 to 37.1 in.), with the six-year average of 714 mm (28.1 in.) being less than normal (ISU-AAERC, 1996-2001). These data indicate that observed variations in rainfall amounts may have been a factor affecting crop yields and nutrient accumulations in the soil profile.

Table 5. Seasonal rainfall (mm) total and annual average values for the six-year study period (1996-2001).

Rainfall	1996	1997	1998	1999	2000	2001	Average [a]
mm	963	668	776	884	461	550	714
Average [b]	824	824	824	824	824	824	

[a] Six-year average (ISU-AAERC, 1996-2001)
[b]Annual average (NOAA, 1996-2001)

Residual Soil P (RSP)

Figure 1 shows the effect of N-management practices on RSP for corn plots averaged over the six-year project period for two soil profile depth increments (0-0.15 and 0.15-0.30 m). The amounts of accumulated RSP ranged from 32.6 kg ha^{-1} (FI1) to 104.1 kg ha^{-1} (WB2) among treatments for the 0-0.15 m depth (figure 1). Amounts of RSP in WB2 and SI2 plots also were significantly higher ($p \leq 0.05$) than UAN and other manure treated plots, indicating the effects of application timing and higher manure rate on the amount of RSP. The higher RSP accumulations in manure plots versus UAN plots were attributed to the contribution of manure to available P. Lindo et al. (1993) found that large applications of P to soil are generally subjected to rapid fixation. The effect of mineralization of organic P also contributed to greater accumulation in the double-rate (FI2, WB2, and SI2) plots. However, the 0.15-0.30 m depth plots (figure 1) show that only SI2 plots (44.2 kg ha^{-1}) had significantly higher ($p \leq 0.05$) P accumulation.

It is well known that surface and near-surface applied P generally adsorbs to soil particles and accumulates in the top layer (0-0.30 m) of the soil profile (Chang et al., 1991; Gangbazo et al., 1999). A similar trend of P accumulation was observed during this study indicating that the 0-0.15 m depth increment had significantly higher ($p \leq 0.05$) RSP than the 0.15-0.30 m depth increment of the soil profile. Eghball et al. (1996) and Graetz et al. (1999) also reported significantly higher accumulation and movement of P from 0-0.15 m depth to deeper depths were from highly-manured plots. However, Tabbara (2003), Gessel et al. (2004), Allen and Mallarino (2008), and Ball Coelho (2007) found that incorporated manure significantly reduced runoff P losses.

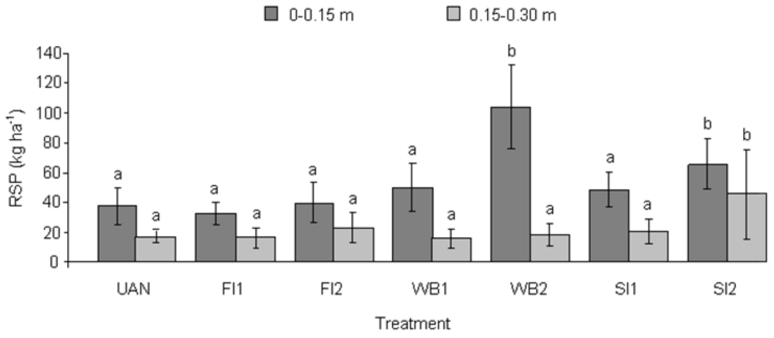

Figure 1. Effect of N-management practices on residual soil phosphorus (RSP [kg ha^{-1}]) at 0-0.15 m and 0.15-0.30 m soil profile depths for corn plots averaged for six years (1996-2001). Different letters indicate significant differences ($p \leq 0.05$) among treatments within selected soil depths and error bars represent ± one standard deviation of the mean.

The cumulative effect of rate, timing, and method of manure application was compared for all six years on RSP in the 0-0.30 m soil profile for corn plots (tables 6 and 7). Table 6 indicates no significant difference ($p \leq 0.05$) in a comparison of single rate (SR) plots (six-year average of SR plots FI1, WB1, and SI1) and the UAN treatment. For double rate (DR) plots (six-year average of DR plots FI2, WB2, and SI2) versus UAN, RSP was significantly higher ($p \leq 0.05$) at 44.8% for DR plots. Sallade and Sims (1997), Novak et al. (2000), and Gessel et al. (2004) reported similar results for significant RSP accumulation in the soil profile. The amount of RSP also was significantly higher ($p \leq 0.05$) by 38% for DR versus SR manure rates (97.9 versus 60.7 kg ha^{-1}, respectively) for corn plots (table 6). Similarly, Qian and Schoenau (2000) found less accumulation of P in soil from SR versus DR manure applications.

Comparison of SI versus FI and WB versus FI treatments for corn plots averaged over six years and manure application rates showed significantly higher ($p \leq 0.05$) accumulations for RSP in SI and WB treatments, 30.6% and 33.8% respectively, compared to the FI treatment (table 6). However, comparison of SI versus WB showed no significant differences ($p \leq 0.05$) in manure application method and/or timing for corn plots. Daverede et al. (2004) determined that injected manure reduced runoff P losses, decreased runoff volumes, and increased time to runoff, minimizing potential risk of surface water contamination. Tables 6 and 8 show that RSP was significantly higher ($p \leq 0.05$) by 23.1% for DR versus SR (73.8 vs. 56.7 kg ha^{-1}, respectively) for soybean plots. The RSP for soybean plots also was significantly higher ($p \leq 0.05$) by 29.6% for SI versus FI (74.3 vs. 52.3 kg ha^{-1}, respectively), and RSP was significantly higher ($p \leq 0.05$) by 28.8% for WB versus FI (73.5 vs. 52.3 kg ha^{-1}, respectively).

Table 6. Comparison of percent differences (%diff) and p-values of N-management practices on residual soil phosphorus (RSP) and residual soil nitrogen (RSN) at 0-0.30 m depth in the soil profile for corn and soybean plots averaged over six years (1996-2001).

Treatment [a]	Corn				Soybean			
	RSP		RSN		RSP		RSN	
Contrast [b]	% diff [c]	p-value	% diff.	p-value	% diff.	p-value	% diff.	p-value
SR vs. UAN	10.9	ns [d]	-8.4	ns	-1.2	ns	-0.6	ns
DR vs. UAN	44.8	≤ 0.05	31.0	≤ 0.05	22.2	≤ 0.05	3.8	ns
DR vs. SR	38.0	≤ 0.05	36.3	≤ 0.05	23.1	≤ 0.05	4.4	ns
SI vs. FI	30.6	≤ 0.05	26.5	≤ 0.05	29.6	≤ 0.05	14.3	≤ 0.01
WB vs. FI	33.8	≤ 0.05	8.0	ns	28.8	≤ 0.05	16.2	≤ 0.01
SI vs. WB	-4.9	ns	20.0	ns	1.1	ns	-2.2	ns

[a] UAN = UAN application single rate (168 kg N ha^{-1}), SR, DR = Average across time and method of all manure applied plots with single (168 kg N ha^{-1}) and double rate (336 kg N ha^{-1}), respectively. FI = Average across rates of all manure injected plots in Fall, WB = Average across rates of all manure broadcast plots in Winter, SI = Average across rates of all manure injected plots in Spring.

[b] Contrast analysis by using SAS software

[c] % diff = Percent difference between treatments, e.g. SR vs. UAN = (1-UAN/SR) x 100

[d] ns = Not significant ($p \leq 0.05$)

Tables 7 and 8 show the cumulative effect of manure applications on RSP in corn and soybean plots, respectively, for the 0-0.30 m soil profile. It depicts a general trend of accumulation for RSP with time (1996 to 2001) in the soil profile for the plots which received DR versus SR. The RSP was found to be the highest, 207.6 kg ha-$^{-1}$, in the WB2 plot (table 7), when compared with the other treatment plots. Qian and Schoenan (2000) also found less accumulation of P in single application of manure in the soil. Manure application in the fall consistently resulted in less accumulation of RSP in the soil profile than the winter and spring applications (table 7). One of the factors that significantly affected the residual amounts of nutrients could be the movement of nutrients to deeper depths from November to April due to the post-harvest rainfall and snow-melt infiltration.

Table 7. Effect of N-application management practices by year on residual soil phosphorus (RSP [kg ha^{-1}]) at 0-0.30 m soil profile depth for corn plots.

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	54.4bc [a]	33.0c	58.6bc	67.2bc	53.8c	56.9c	53.9c
FI1	38.7c	54.2bc	38.4c	56.6c	44.4c	58.9c	48.5c
FI2	53.1b	60.5bc	52.1c	74.1bc	54.7c	76.6c	61.8bc
WB1	68.3ab	66.5ab	55.5bc	83.6bc	58.6bc	58.2c	65.1bc
WB2	82.7a	89.1ab	84.7bc	152.2a	115.2ab	207.6a	121.9a
SI1	67.1ab	55.3bc	66.8bc	63.1bc	68.9abc	88.8bc	68.3b
SI2	57.9c	107.2a	106.6a	104.2b	120.0a	163.4ab	109.9a
Average	60.3	66.5	66.1	85.8	73.6	101.5	75.7
CV [b]	18.4	43.3	25.4	30.4	43.6	44.5	33.0
Stderr [c]	19.1	25.7	14.9	16.9	9.5	21.3	14.2
LSD [d] (0.05)	19.8	51.3	29.9	46.5	57.2	80.4	16.6

[a] Means with the same letters in column are not significantly different ($p \leq 0.05$)

[b] Coefficient of variance; [c] Standard error; [d] Least significant difference

Table 8. Effect of N-application management practices by year on residual soil phosphorus (RSP [kg ha^{-1}]) at 0-0.30 m soil profile depth for soybean plots.

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	41.9a [a]	37.2b	63.1ab	89.1a	60.3c	52.8c	57.4bc
FI1	37.7a	39.6b	42.5b	40.8c	55.1c	46.2c	43.6d
FI2	41.8a	41.7b	61.1ab	52.5bc	57.3c	59.7c	52.3cd
WB1	52.1a	68.5a	42.5b	66.8abc	73.5bc	56.4c	60.2cb
WB2	50.9a	78.0a	62.7ab	87.8a	102.2ab	139.5a	86.8a
SI1	47.1a	71.6a	79.8a	72.0ab	69.1bc	58.5c	66.3b
SI2	33.9a	60.2ab	80.2a	85.7a	136.8a	96.7b	82.2a
Average	43.6	56.7	61.8	70.6	79.2	72.8	64.1
CV [b]	32.4	24.8	26.9	24.5	27.9	27.7	24.3
Stderr [c]	15.0	26.7	16.3	10.9	21.8	15.7	15.9
LSD [d] (0.05)	25.2	25.0	29.7	30.8	39.3	35.9	10.4

[a] Means with the same letters in column are not significantly different ($p \leq 0.05$)

[b] Coefficient of variance; [c] Standard error; [d] Least significant difference

Residual Soil N (RSN)

When averaged over six years for corn plots, the amount of RSN for 0-0.15 m depths ranged from 7.5 to 14.5 kg ha^{-1} among the treatments (figure 2). The RSN for SI2 (14.5 kg ha^{-1}) and WB2 (13.4 kg ha^{-1}) treatments were significantly higher ($p \le 0.05$) than all other treatments. However, timing of application did not affect RSN for the single rate (FI1, WB1, and SI1) plots. For the 0.15-0.30 m depth, only the SI2 (12.4 kg ha^{-1}) treatment was found to be significantly higher ($p \le 0.05$) than the other treatments (figure 2). Zhu and Fox (2003) determined that RSN in the top 0.25 m soil layer after harvest was not significant at 0-100 kg N ha^{-1}, but was significant at the higher 100-200 kg N ha^{-1} rate. As shown in table 6, significantly higher ($p \le 0.05$) accumulation (26.5%) was observed for RSN in the SI versus FI treatments in corn plots. However, Loecke et al. (2004) found mean N-supply efficiency (defined as N-fertilizer equivalency value as a percentage of total N applied) was 24.3% and 10.9% for fall- and spring-applied swine manure, respectively. The reason for this trend may be that manure applications in fall allow more time (approximately one year) for manure decomposition, leaching, denitrification, and other physical and chemical activities than spring or winter applications (six to eight months). Fall manure applications also include additional time for crop uptake of nutrients that occurs before annual soil sampling.

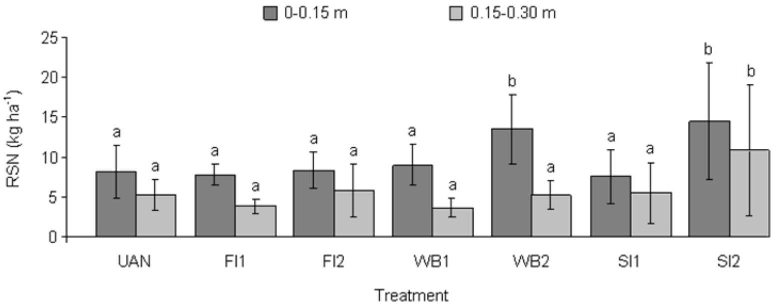

Figure 2. Effect of N-management practices on residual soil nitrogen (RSN [kg ha^{-1}]) at 0-0.15 m and 0.15-0.30 m soil profile depths for corn plots averaged for six years (1996-2001). Different letters indicate significant differences ($p \le 0.05$) among treatments within selected soil depths and error bars represent ± one standard deviation of the mean.

Significantly higher ($p \le 0.05$) RSN at 26.5% was determined for SI versus FI treatments in corn plots (table 6). Nevertheless, the comparison of WB versus FI and SI versus WB treatments for RSN showed no significant differences ($p \le 0.05$) for manure application method and/or timing for corn plots (tables 6 and 9). The primary reason could be that winter and spring application timings were approximately one month apart for most of the study years. Relatively colder weather conditions during winter and spring months (November to April) also limited soil-water functions such as manure decomposition, leaching, surface water runoff, subsurface drainage flow, and reduction in microbial activity.

Similarly, Gilley et al. (2007) found that significant N leaching occurred after harvest (September 30) from corn residue and resulted in increased NO_3-N in runoff. Other studies also determined that NO_3-N concentrations and losses in drainage from corn were greatest for fall-applied N (Randall et al., 2003; Randall and Vetsch, 2005). Zhu and Fox (2003) reported that while leaching potential of RSN was similar for corn and soybean at recommended N rates, RSN leaching potential was greater under soybean than corn at less than 100 kg N ha^{-1}. Soil data from soybean plots (table 1) also reflected effects of the previous year's manure/UAN applications on RSN in the 0-0.30 m soil profile (table 10). Randall et al. (2003) found that NO_3-N losses from soybean were affected more by residual soil NO_3-N following corn than by N treatments alone.

Table 9. Effect of N-application management practices by year on residual soil nitrogen (RSN [kg ha^{-1}]) at 0-0.30 m soil profile depth for corn plots.

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	13.7b [a]	3.3a	7.8b	14.0ab	27.8a	17.8bc	14.1bc
FI1	11.1b	2.8a	8.1b	15.9ab	22.5a	12.8c	12.2c
FI2	8.6b	15.1a	12.4ab	15.1ab	24.5a	13.8c	14.9bc
WB1	12.4b	2.7a	7.7b	19.2ab	20.1a	16.2c	13.1bc
WB2	16.6b	4.2a	14.1ab	22.9a	32.8a	26.0ab	19.4b
SI1	16.6b	17.4a	10.6ab	10.4b	14.2a	13.2c	13.7bc
SI2	31.2a	28.9a	16.2a	18.1ab	36.1a	30.8a	26.9a
Average	15.7	10.6	11.0	16.5	25.4	18.6	16.3
CV [b]	29.4	152.6	40.7	32.2	53.0	28.8	59.3
Stderr [c]	7.1	5.6	5.9	1.3	3.6	3.8	1.3
LSD [d] (0.05)	8.2	28.9	7.9	9.4	24.0	9.6	6.4

[a] Means with the same letters in column are not significantly different ($p \leq 0.05$)
[b] Coefficient of variance; [c] Standard error; [d] Least significant difference

Table 10. Effect of N-application management practices by year on residual soil nitrogen (RSN [kg ha-1]) at 0-0.30 m soil profile depth for soybean plots.

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	11.7b [a]	5.6a	11.7a	23.2a	18.0a	21.3bc	15.2bc
FI1	10.3b	3.5a	10.0a	21.3ab	22.2a	19.5bc	14.4bc
FI2	9.6b	3.1a	10.6a	19.3ab	21.0a	19.0bc	13.8c
WB1	11.1b	3.7a	12.2a	22.9a	24.2a	17.5c	15.2abc
WB2	17.4a	4.1a	13.2a	18.4b	26.4a	25.8b	17.6a
SI1	11.1b	4.7a	10.5a	22.1ab	25.5a	20.6bc	15.8abc
SI2	11.7b	2.7a	14.6a	20.1ab	26.8a	22.0ab	16.3ab
Average	11.8	3.9	11.8	21.0	23.4	20.8	15.5
CV [b]	20.6	42.8	27.9	11.5	22.2	11.2	22.2
Stderr [c]	3.5	0.2	3.2	1.4	3.4	1.6	0.3
LSD [d] (0.05)	4.3	2.9	5.8	4.3	9.2	4.1	2.2

[a] Means with the same letters in column are not significantly different ($p \leq 0.05$)
[b] Coefficient of variance; [c] Standard error; [d] Least significant difference

The deep soil core (0-1.22 m) RSN analysis in 1996 and 2000 (during corn years) showed that effects of rate and timing were significant ($p \leq 0.05$) on RSN at the 0-0.15 and 0.91-1.22 m depths in the soil profile (table 11). These data also show that five years (1996-2000) of manure application significantly increased ($p \leq 0.05$) the amount of RSN for the 0-0.15 m depth of the soil profile (figure 2; tables 9 and 11). The amount of RSN also significantly increased ($p \leq 0.05$) with increasing depth, indicating UAN- and manure-derived NO$_3$-N movement through the soil profile. The differences in RSN between DR versus SR were found to be significant ($p \leq 0.05$) for soil depth increments 0-0.5, 0.30-0.61, 0.61-0.91, and 0.91-1.22 m (table 11). The SI versus FI treatment differences also were significant ($p \leq 0.05$) at the 0-0.15 and 0.91-1.22 m soil depth increments (table 11).

Table 11. Comparison of p-values for N-management practices on residual soil nitrogen (RSN) at selected depths in the soil profile for corn plots averaged over two years (1996 and 2000).

Treatment	RSN				
	p-value				
	0-0.15 m	0.15-0.30 m	0.30-0.61 m	0.61-0.91 m	0.91-1.22 m
SR vs. UAN	ns [a]	ns	ns	ns	ns
DR vs. UAN	ns	ns	ns	≤ 0.05	ns
DR vs. SR	≤ 0.05	ns	≤ 0.05	≤ 0.05	≤ 0.05
SI vs. FI	≤ 0.05	ns	ns	ns	≤ 0.05
WB vs. FI	ns	ns	ns	ns	≤ 0.05
SI vs. WB	≤ 0.05	ns	ns	ns	ns

[a] ns = Not significant ($p \leq 0.05$)

The two-year (1996 and 2000) RSN average manure application rate for corn plots was used to evaluate the effect of application timing. These RSN averages resulted in significantly higher ($p \leq 0.05$) SI (73.4 kg ha^{-1}) and WB (67.1 kg ha^{-1}) treatments of 34.2% and 27.9%, respectively (table 11). The SI and WB treatments also were significantly higher ($p \leq 0.05$) than FI (48.3 kg ha^{-1}) at the 1.22 m soil profile depth. The comparison of RSN for application rates DR versus SR (82.7 versus 43.1 kg ha^{-1}, respectively) also showed a significant difference ($p \leq 0.05$) between the treatments (table 11). Overall, these results indicate that RSN was found in both UAN- and manure-applied plots.

The accumulation of RSN at selected depths over time may be attributed to N applications as UAN or swine manure and rainfall conditions. The reduced NO_3-N transport to deeper depths (0.61-0.91 and 0.91-1.22 m depth increments) for year 2000 may have been a function of less than average rainfall (461 mm [18.1 in.]; table 5) during the growing season. These drier conditions could have limited N-transport since NO_3-N accumulation in the soil profile and its leaching to deeper depths has been cited in many studies (Jokela, 1992; Weed, 1996; Mehdi and Madramooto, 1999; Randall et al., 1999; Bakhsh et al., 2000). Randall et al. (2003) found that NO_3-N concentrations in drainage water were two to three times greater in the two years following a three-year dry period compared with preceding and succeeding years; and van Es et al. (2006) reported that high levels of concern are associated with periods following dry growing seasons since high residual-N levels contribute greatly to high leaching concentrations. Bakhsh et al. (2005) also suggested the need for better management of swine manure application during wet and dry growing seasons to reduce NO_3-N leaching into shallow groundwater systems to avoid contamination of drinking water supplies.

Averaged values from figure 3 shows significant reductions ($p \leq 0.05$) in RSN at the 0-1.22 m soil depth from spring double-rate (SI2) application times between two years (1996 and 2000) for corn plots, and table 11 indicates significant differences ($p \leq 0.05$) in RSN in the 0.91-1.22 m soil depth increment. Chang et al. (1991) reported significant N accumulation to a depth of 0.50 m after 11 years of manure applications. Figure 3 shows the cumulative effect of N-management on average RSN in the 0-1.22 m soil profile with time (1996 versus 2000). Increases in accumulation of RSN from 1996 to 2000 ranged from 47.6 to 150.4 kg ha^{-1} for the manure treatments, with a significant increase ($p \leq 0.05$) in the WB2 treatment in the 0-1.22 m soil profile. There also was a significant increase ($p \leq 0.05$) in RSN (29.6 to 65.1 kg ha^{-1}) from 1996 to 2000 for the UAN treatment (figure 3), and the highest RSN accumulation with time (47.9 to 150.0 kg ha^{-1}) was found in the WB2 treatment (figure 3).

The accumulation of RSN in the relatively drier year of 2000 could be attributed to low crop N uptake, N mineralization, and below average rainfall. When these data from figure 3 were averaged over the two years of sampling (1996 and 2000), WB2 and SI2 treatments had the highest RSN (99.1 and 85.8 kg ha^{-1}, respectively) and were found to be significantly higher ($p \leq 0.05$) than the other treatments. The FI1 treatment had the lowest RSN (33.3 kg ha^{-1}) in the soil profile. Although the FI2 treatment had a lower RSN level (63.4 kg ha^{-1}) versus the WB2 and SI2 treatments, the differences were not significantly different ($p \leq 0.05$). These data from year 2000 suggest that the amount of NO_3-N available for leaching in the fall can be significant due to the lack of crop N uptake, low evapotranspiration, below average rainfall, and limited microbial activity. In addition, when averaged over the treatments, an increase in RSN accumulation was observed in 0-0.30 m profile with time (table 9). RSN was found to be the highest in the year 2000 (25.4 kg ha^{-1}) for corn plots. It is verification of the effect of rainfall on the leaching of RSN through the soil profile during a dry year (the annual rainfall was the lowest during the six-year study with 461 mm [18.1 in.] for year 2000). Randall et al. (2003) and Randall and Vetsch (2005) suggested that NO_3-N losses from a corn-soybean rotation into subsurface drainage can be reduced by approximately 14% using the spring manure application timing. Another approach to reduce higher N levels in runoff involves using a rye (*Secale cereale* L.) cover crop. Parkin et al. (2006) determined that this strategy increased N retention and reduced cumulative N_2O emissions and N-load in drainage water when manure was applied to soils.

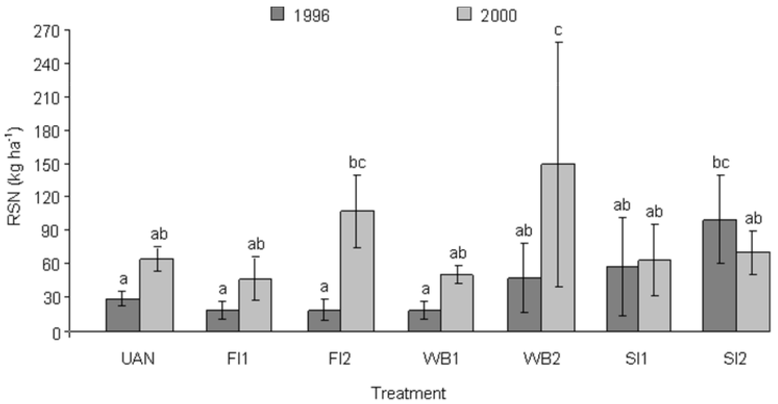

Figure 3. Effect of N-management practices on residual soil nitrogen (RSN [kg ha^{-1}]) between two years (1996 and 2000) for corn plots. Different letters indicate significant differences ($p \leq 0.05$) among treatments within years and error bars represent ± one standard deviation of the mean.

Percent Organic Matter (OM%), pH, and Carbon:Nitrogen (C:N) Ratio

The six-year average of soil OM% for 0-0.15 and 0.15-0.30 m soil depths for corn plots ranged from 2.5% (SI2; 0.15-0.30 m depth) to 3.4% (SI1; 0-0.15 m depth) (figure 4). Average OM% in the SI1 treatment was significantly higher ($p \leq 0.05$) than other treatments (figure 4) and effects of N-management on OM% in the 0-0.30 m depth soil profile for corn plots was significantly different ($p \leq 0.05$) among treatments only in 1996 and 1997. However, cumulative OM% did not significantly increase ($p \leq 0.05$) for both corn and soybean plots during the six-year study (1996-2001). Several studies have shown that increases in soil OM% can be achieved by long-term applications of UAN or organic manures (Lal and Kang, 1982; Sanchez et al., 1989; Haynes and Williams, 1992). Haynes and Naidu (1998) also reported that manure application increased OM content in the soil profile. However, Whalen and Chang (2002) found that long-term manure application in southern Alberta, Canada increased soil C, N, and P concentrations and reduced OM aggregate size due to manure dispersive agents, possibly increasing the risk of soil and nutrient loss through wind erosion.

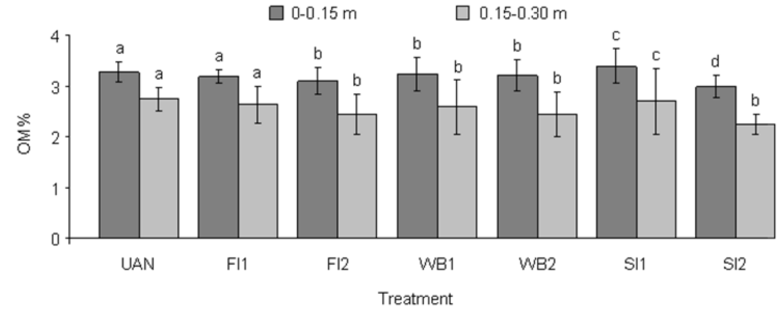

Figure 4. Effect of N-management practices on percent organic matter (OM%) at 0-0.15 m and 0.15-0.30 m soil profile depths for corn plots averaged for six years (1996-2001). Different letters indicate significant differences ($p < 0.05$) among treatments within selected soil depths and error bars represent ± one standard deviation of the mean.

The effect of UAN and manure applications on pH in the soil profile also was evaluated during the six-year study period, resulting in no significant differences ($p \leq 0.05$) for average soil pH among treatments for both corn and soybean plots.

Soil C:N ratio for 0-1.22 m soil profile depth was determined for project study years 1997, 1998, and 1999 and was found to be approximately 15 at the 0.61 m depth for all treatments; and significantly increased ($p \leq 0.05$) below the 0.61 m depth as a function of lower percent N deeper in the soil profile during the three sampling years. Sauerbeck (1982) found that the greatest increase in soil organic carbon included a manure treatment when compared with straw and composted manure treatments. However, the cumulative effect of manure application on C:N ratio in the 0-1.22 m depth range averaged over three years (1997-1999) indicated that application rate, timing, and method did not significantly affect ($p \leq 0.05$) C:N ratio in the soil profile.

Corn and Soybean Yield Analysis

Crop yield analysis results indicate that the application of N-management practices affected corn yields in all six years of the study (1996-2001). Average corn yields ranged from 5,275 kg ha^{-1} for UAN (control) in 2001 to 11,183 kg ha^{-1} for SI2 in 1997 (table 12). Significant reductions ($p \le 0.05$) in average corn yields during 2000 and 2001 may have been caused by below-normal seasonal rainfall for the 2000 and 2001 growing seasons. However, using the same research site during roughly the same time period as this study, Loecke et al. (2004) determined that fall 2001 applications of swine manure increased corn grain yield more than the spring application time.

Table 12. Comparison of corn yield (kg ha^{-1}) for individual N-management treatments by year (1996-2001).

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	7,923	7,724	9,860	8,442	7,959	5,275	7,864
FI1	7,858	9,364	10,149	8,320	8,505	9,122	8,886
FI2	8,226	10,565	10,004	9,185	9,227	10,305	9,585
WB1	9,553	8,782	9,104	8,177	8,093	8,310	8,670
WB2	10,599	9,681	9,612	8,738	8,702	9,677	9,502
SI1	9,958	9,557	9,330	8,312	8,087	9,351	9,099
SI2	10,002	11,183	10,924	9,681	8,646	10,122	10,093

Table 13. Comparison of soybean yield (kg ha^{-1}) for individual N-management treatments by year (1996-2001).

Treatment	1996	1997	1998	1999	2000	2001	Average
UAN	2,658	3,071	2,897	2,765	2,037	1,894	2,554
FI1	2,760	2,955	2,658	2,700	2,064	1,930	2,511
FI2	2,751	2,859	2,850	2,845	2,325	2,233	2,644
WB1	2,859	2,856	2,890	2,968	2,102	2,173	2,641
WB2	2,745	3,314	2,863	3,176	2,309	2,354	2,794
SI1	2,756	3,158	2,734	2,687	1,865	1,965	2,528
SI2	2,738	3,265	3,035	2,993	2,289	2,506	2,804

A trend of increased corn yields from the higher double-rate (DR) manure application plots (FI2, SI2, and WB2) versus the single-rate (SR) plots (FI1, SI1, and WB1) was observed throughout the study period where the effect of DR versus SR was significantly different ($p \le 0.05$) for every year except 1996 and 1998 (table 14). The average corn yield for DR plots also was significantly higher ($p \le 0.05$) at 19.1% than UAN application plots and similar results of N-management practices on crop yields have been documented by other researchers (Bundy, 1986; Blaylock and Cruse, 1992; Jokela and Randall, 1989). The effect of manure application timing (SI versus FI treatments) on corn yields was significantly different ($p \le 0.01$) in 1996 and the methods of application (SI versus WB) resulted in significantly higher ($p \le 0.05$) corn yields for SI plots during the years 1997 and 2001 (table 14). Blaylock and Cruse (1992) found higher corn yields and N-recovery when UAN was injected versus broadcast applications in Iowa and Daverede et al. (2004) reported that injected manure also reduced runoff P losses.

Table 14. Comparison of p-values for N-management practices on corn yield by year (1996-2001).

Treatment	Corn yield					
	p-value					
	1996	1997	1998	1999	2000	2001
SR vs. UAN	0.01	$\le$ 0.01	ns	ns	ns	$\le$ 0.05
DR vs. UAN	$\le$ 0.01	$\le$ 0.01	ns	ns	0.02	$\le$ 0.05
DR vs. SR	ns [a]	$\le$ 0.01	ns	0.03	0.03	$\le$ 0.05
SI vs. FI	$\le$ 0.01	ns	ns	ns	ns	ns
WB vs. FI	$\le$ 0.01	ns	ns	ns	ns	$\le$ 0.05
SI vs. WB	ns	0.01	ns	ns	ns	$\le$ 0.05

[a] ns = Not significant ($p \le 0.05$)

Table 15. Comparison of p-values for N-management practices on soybean yield by year (1996-2001).

Treatment	Soybean yield					
	p-value					
	1996	1997	1998	1999	2000	2001
SR vs. UAN	ns [a]	ns	ns	ns	ns	ns
DR vs. UAN	ns	ns	ns	ns	ns	≤ 0.05
DR vs. SR	ns	ns	ns	≤ 0.05	≤ 0.05	≤ 0.05
SI vs. FI	ns	≤ 0.05	ns	ns	ns	ns
WB vs. FI	ns	ns	ns	0.01	ns	ns
SI vs. WB	ns	ns	ns	ns	ns	ns

[a] ns = Not significant ($p \leq 0.05$)

When averaged over the six years (1996-2001), SI2 yield for corn plots (table 16) was significantly higher ($p \leq 0.05$) among all treatments at 10,093 kg ha^{-1} (table 12). The average long-term corn yield in the area is 9,350 kg ha^{-1} (IAS, 2002). The lowest average corn yield was from the UAN plots (7,864 kg ha^{-1}) (table 12). While average corn yields for all manure treatments were improved above the UAN treatment over the six-year study period (table 16), the SI1 treatment produced significantly higher ($p \leq 0.05$) yields (9,099 kg ha^{-1}) (table 12) among the other two SR manure application treatments (FI1 and WB1).

Table 16. Comparison of percent differences (%diff) and p-values for N-management practices on crop yields averaged over six years (1996-2001).

Treatment	Corn yield		Soybean yield	
	% diff	p-value	% diff	p-value
SR vs. UAN	11.5	≤ 0.01	0.5	ns
DR vs. UAN	19.1	≤ 0.01	6.5	≤ 0.05
DR vs. SR	8.6	≤ 0.01	6.0	≤ 0.05
SI vs. FI	3.7	0.02	4.2	ns
WB vs. FI	-1.6	ns [a]	6.5	≤ 0.05
SI vs. WB	5.3	≤ 0.01	-2.4	ns

[a] ns = Not significant ($p \leq 0.05$)

Mallarino and Wittry (2010) found that liquid swine manure P always increased corn and soybean grain yield with soil test P (STP) very low (< 16 mg Bray-P1 kg^{-1}) and only in three of nine sites with STP at optimum level (16-20 mg P kg^{-1}). Analysis of soybean yields by year showed that soybean yield was not significantly different ($p \leq 0.05$) due to the previous year's N-management practices (tables 13 and 15). However, when yields from soybean followed by corn were averaged over the six years, WB2 and SI2 treatment plots had significantly higher ($p \leq 0.05$) yields than the other treatments (tables 13 and 16).

Although N-management practices were not conducted on soybean plots, below-average rainfall conditions may have affected soybean yields during 2000 and 2001. Average soybean yields ranged from 1,865 kg ha^{-1} for SI1 in 2000 to 3,314 kg ha^{-1} for WB2 in 1997 (table 13). The long-term average soybean yield in the area is 2,890 kg ha^{-1} (IAS, 2002). Residual effects of N-management practices were significantly different ($p \leq 0.05$) for all years except 1996 (first year of the study).

Summary and Conclusions

This study evaluated long-term effects of several liquid swine manure application methods on post-harvest soil nutrients and crop yields, and discussed potential water quality implications in a corn-soybean rotation. Six consecutive years (1996-2001) of UAN and manure applications to soil showed a trend of significant increases in RSP and RSN in the 0-0.30 and 0-1.22 m soil profile, respectively. Another trend of significantly higher crop yields was observed with the higher manure double-rate (DR [336 kg N ha^{-1}]) application versus the single-rate (SR [168 kg N ha^{-1}]) application. However, there were no significant effects on soil OM%, pH, and C:N ratio after six years of UAN/manure applications.

The two manure SR and DR application treatments significantly affected RSP and RSN in the soil profile. The trend of higher accumulation of RSP and RSN for the higher DR manure application was consistent throughout the study period, indicating there may have been more manure-P and crop available-N applied than the crop demanded. Consequently, a greater potential for significant environmental pollution exists for the higher DR manure application. While the amount of annual rainfall can affect crop nutrient uptake, leaching, and transport; the accumulation of average soil profile RSN levels was significantly higher for the years 2000 and 2001 with below-average annual rainfall.

A comparison of injection versus broadcast manure application methods when averaged over project years and application rates showed more accumulation of RSP from the broadcast method and more RSN from the injection method in the soil profile. This could be a result of available P and N from manure and appeared to be related to conservation of NH_3 and mineralization of organic P and N, increasing the accumulation of residual P and N in the soil profile. The application methods also affected corn yield with winter broadcast method resulting in the lowest yield (9,086 kg ha^{-1}) and spring injection method produced the highest yield (9,596 kg ha^{-1}) when averaged over study years and manure application rates.

The analysis of three manure application timings (fall, winter, and spring) illustrated that fall application had the lowest average RSP and RSN in the soil profile and lower crop yield. This demonstrated that fall manure application has the potential to be a significant threat to the soil-water environment due to reduction of crop N and P utilization, microbial activity, post-harvest rainfall, and evapotranspiration from November to April. Consequently, subsequent accumulations of nutrients in soil could move through the profile to deeper depths, possibly contaminating shallow groundwater.

The six-year average corn yield was significantly higher (10,093 kg ha^{-1}) when manure was injected with the higher DR application in spring. The lowest average corn yield was found with the UAN plots (7,864 kg ha^{-1}). Although no manure and UAN were applied to soybean plots, residual effect of N-management also increased soybean yields for the DR application. Below-average annual rainfall conditions during project years 2000 and 2001 also may have reduced corn and soybean yields.

Overall, these results indicate an accumulation of large amounts of RSP and RSN in higher DR manure application plots. Timing of manure application also influenced nutrient accumulation and leaching through the soil profile. Changing manure application time from fall to spring significantly increased average corn yield up to 3.7%. The reduction in corn yield for the fall application may have been due to denitrification of available N, low nutrient level in the root zone, movement of NO_3-N to deeper depths with infiltrated water, and leaching to shallow groundwater (subsurface drainage tile line was 1.2 m from the soil surface). These results tend to indicate more nutrient accumulation was observed in spring and winter applications plots versus fall application plots. However, some studies indicated increased nutrient accumulation in fall and increased corn grain yield from fall N application, possibly due to below-average rainfall conditions that were experienced during this study in years 2000 and 2001.

The results of this study could provide better N-management information for Midwest US farmers and livestock producers. Manure N-management practices must be evaluated in the context of economic and other production constraints faced by farmers and livestock producers. The fall application time has been a common practice used to avoid issues related to spring application such as minimal storage capacity, wet soil, soil compaction, and high labor and equipment costs. However, potentially higher yields obtained using the spring versus fall application time should be considered to possibly offset increased operating expenses and management limitations.

Among N-management practices evaluated in this study, manure injections in fall and spring resulted in average corn yields ranging from 9,236 kg ha^{-1} to 9,596 kg ha^{-1}, respectively, indicating the spring application time may be a more effective and profitable practice. Moreover, it is important to further investigate the effects of fall application on shallow groundwater to enhance the establishment of appropriate best management practices to minimize potential threats to the soil-water environment. It also is suggested that a long-term manure application study to determine nutrient mass balance values for corn and soybean under other crop production systems could provide useful data and information for researchers and farmers in the decision-making process. Other future long-term studies might include documenting potential effects of climate change, variable economic conditions, livestock dietary impacts on soil N cycling (Paschold et al., 2008; Powell and Grabber, 2009), and the use of matrix-based fertilizers (Entry et al., 2010) on N-management practices, N and P leaching, and corn-soybean yields.

References

Allen, B.L., and A.P. Mallarino. 2006. Relationships between extractable soil phosphorus and phosphorus saturation after long-term fertilizer or manure application. *Soil Sci. Soc. America J.* 70(2):454-463.

Allen, B.L., and A.P. Mallarino. 2008. Effect of liquid swine manure rate, incorporation, and timing of rainfall on phosphorus loss with surface runoff. *J. Environ. Quality* 37(1):125-137.

Andrews, W.F., and R.O. Dideriksen. 1981. *Soil Survey of Boone County, Iowa.* Washington DC: USDA Soil Conservation Service.

Ahmed, S.I., and R.S. Kanwar. 1997. Effect of swine manure and other N-management practices on residual soil NO_3-N under corn-soybean rotation. ASAE Paper No. 972146. St. Joseph, MI: American Society of Agricultural Engineers.

Bakhsh, A., R.S. Kanwar, and D.L. Karlen. 2005. Effects of liquid swine manure applications on NO_3-N leaching losses to subsurface drainage water from loamy soils in Iowa. *Agric. Ecosystems Environ.* 109(1-2):118-128.

Bakhsh, A., R.S. Kanwar, D.L. Karlen, C.A. Cambardella, T.S. Colvin, T.B. Moorman, and T.B. Bailey. 2000. Tillage and nitrogen management effects on crop yield and residual soil nitrate. *Trans. ASAE* 43(6):1589-1595.

Ball Coelho, B.R., R.C. Roy, E. Topp, and D.R. Lapen. 2007. Tile water quality following liquid swine manure application into standing corn*. J. Environ. Quality* 36(2):580-587.

Barbazan, M.M., A.P. Mallarino, and J.E. Sawyer. 2009. Liquid swine manure phosphorus utilization for corn and soybean production. *Soil Sci. Soc. America J.* 73(2):654-662.

Black, C.A. 1965. Phosphorus soluble in dilute acid-flouride, pages 1040-1041. In *Methods of Soil Analysis: Physical and mineralogical properties, including statistics of measurement and sampling.* Part 2. American Society of Agronomy.

Blanchet, L.M. 1996. Impact of lime application on atrazine, cyanazine, and nitrate transport to subsurface drainage water: A lysimeter study. MS thesis. Ames, Iowa: Iowa State University, Department of Agricultural Engineering.

Blaylock, A.D., and R.M. Cruse. 1992. Ridge-tillage corn response to point-injected nitrogen fertilizer. *Soil Sci. Soc. America J.* 56(2):591-595.

Boddy, P.L., and J.L. Baker. 1990. Conservation tillage effects on nitrate and atrazine leaching. ASAE Paper No. 90-2503. St. Joseph, MI: American Society of Agricultural Engineers.

Bray R. H., and L.T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* 59(1):39-46.

Bundy, L.G. 1986. Review: Timing nitrogen applications to maximize fertilizer efficiency and crop response in conventional corn production. *J. Fertilizer Issues* 3(3):99-106.

Bundy, L.G., T.W. Andraski, and R.P. Wolkowski. 1993. Nitrogen credits in soybean-corn crop sequences on three soils. *Agron. J.* 85(5):1061-1067.

Chang, C., T.G. Sommerfeldt, and T. Entz. 1991. Soil chemistry after eleven annual applications of cattle feedlot manure. *J. Environ. Quality* 20(2):475-480.

Daliparthy, J., S.J. Herbert, L.J. Moffitt, and P.L.M. Veneman. 1995. Herbage production, weed occurrence, and economic risk from dairy manure applications to alfalfa. *J. Prod. Agric.* 8(4):495-501.

Daverede, I.C., A.N. Kravchenko, R.G. Hoeft, E.D. Nafziger, D.G. Bullock, J.J. Warren, and L.C. Gonzini. 2004. Phosphorus runoff from incorporated and surface-applied liquid swine manure and phosphorus fertilizer. *J. Environ. Quality* 33(4):1535-1544.

David, M.B., L.E. Drinkwater, and G.F. McIsaac. 2010. Sources of nitrate yields in the Mississippi River Basin. *J. Environ. Quality* 39(5):1657-1667.

Eghball, B., G.D. Binford, and D.D. Baltenspereger. 1996. Phosphorus movement and adsorption in a soil receiving long-term manure and fertilizer application. *J. Environ. Quality* 25(6):1339-1343.

Entry, J.A., R.E. Sojka, and B.J. Hicks. 2010. Matrix-based fertilizers reduce nutrient and bacterial leaching after manure application in a greenhouse column study. *J. Environ. Quality* 39(1):384-392.

Ferguson, R.B., J.A. Nienaber, R.A. Eigenberg, and B.L. Woodbury. 2005. Long-term effects of sustained beef feedlot manure application on soil nutrients, corn silage yield, and nutrient uptake. *J. Environ. Quality* 34(5):1672-1681.

Fox, R.H., and W.P. Piekielek. 1988. Fertilizer N equivalence of alfalfa, birdsfoot trefoil, and red clover for succeeding corn crops. *J. Prod. Agric.* 1(4):313-317.

Gangbazo, G., A.R. Pesant, D. Cote, G.M. Barnett, and D. Cluis. 1997. Spring runoff and drainage N and P losses from hog-manured corn. *J. American Water Resources Assoc.* 33(2):405-411.

Gangbazo, G., G.M. Barnett, A.R. Pesant, and D. Cluis. 1999. Disposing hog manure on inorganically-fertilized corn and forage fields in southeastern Quebec. *Canadian Agric. Eng.* 41(1):1-12.

Gast, R.G., W.W. Nelson, and G.W. Randall. 1978. Nitrate accumulation in soils and loss in tile drainage following nitrogen applications to continuous corn. *J. Environ. Quality* 7(2):258-261.

Gessel, P.D., N.C. Hansen, J.F. Moncrief, and M.A. Schmitt. 2004. Rate of fall-applied liquid swine manure: Effects on runoff transport of sediment and phosphorus. *J. Environ. Quality* 33(5):1839-1844.

Gilley, J.E., B. Eghball, and D.B. Marx. 2007. Nutrient concentrations of runoff during the year following manure application. *Trans. ASABE* 50(6):1987-1999.

Gilley, J.E., L.M. Risse, and B. Eghball. 2002. Managing runoff following manure application. *J. Soil Water Conserv.* 57(6):530-533.

Graetz, D.A., V.D. Nair, K.M. Portier, and R.L. Voss. 1999. Phosphorus accumulation in manure-impacted Spodosols of Florida. *Agric. Ecosystems Environ.* 75(1-2):31-40.

Haynes, R.J., and R. Naidu. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems* 51(2):123-137.

Haynes, R.J., and P.H. Williams. 1992. Accumulation of soil organic matter and the forms, mineralization potential and plant-availability of accumulated organic sulfur: Effects of pasture improvement and intensive cultivation. *Soil Biol. Biochemistry* 24(3):209-217.

IAS (*Iowa Agricultural Statistics*). 2002. Department of Agronomy, Iowa State University, Ames, Iowa.

ISU-AAERC (Agronomy and Agricultural Engineering Research Center). 1996-2001. Rainfall data for 1996-2001.

Jacobson, L.M., M.B. David, and L.E. Drinkwater. 2011. A spatial analysis of phosphorus in the Mississippi River Basin. *J. Environ. Quality* 40(3):931-941.

Jokela, W.E. 1992. Nitrogen fertilizer and dairy manure effects of corn yield and soil nitrate. *Soil Sci. Soc. America J.* 56(1):148-154.

Jokela, W.E., and G.W. Randall. 1989. Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. *Agron. J.* 81(5):720-726.

Karlen, D.L., G.E. Varvel, D.G. Bullock, and R.M. Cruse. 1994. Crop Rotations for the 21st Century. In *Advances in Agronomy*, Volume 53, pages 1-45. Academic Press, Inc., San Diego, CA.

Kanwar, R.S., J.L. Baker, and D.G. Baker. 1988. Tillage and split N-fertilization effects on subsurface drainage water quality and crop yields. *Trans. ASAE* 31(2):453-461.

Kanwar, R.S., J.L. Baker, and J.M. Laflen. 1985. Nitrate movement through the soil profile in relation to tillage system and fertilizer application method. *Trans. ASAE* 28(6):1802-1807.

Kanwar, R.S., T.S. Colvin, D.L. Karlen, C.A. Camberdella, R.M. Cruse, and C.H. Pederson. 1996. Quality of subsurface drainage water under different agricultural production system. In *Proceedings of the 6th ICID Drainage and Environment Conference*, The Slovenian committee of the ICID 681-687, Ljubljana, Slovenia.

Katupitiya, A., D.E. Eisenhauer, R.B. Ferguson, R.F. Spalding, F.W. Roeth, and M.W. Bobier. 1997. Long-term tillage and crop rotation effects on residual nitrate in the crop root zone and nitrate accumulation in the intermediate vadose zone. *Trans. ASAE* 40(5):1321-1327.

Khaleel, R., K.R. Reddy, and M.R. Overcash. 1980. Transport of potential pollutants in runoff water from land areas receiving animal wastes: a review. *Water Res.* 14(5):421-436.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. *J. Environ. Quality* 23(1):139-147.

Kleinman, P.J.A., and A.N. Sharpley. 2003. Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. *J. Environ. Quality* 32(3):1072-1081.

Kleinman, P.J.A., A.N. Sharpley, B.G. Moyer, and G.F. Elwinger. 2002. Effect of mineral and manure phosphorus sources on runoff phosphorus. *J. Environ. Quality* 31(6):2026-2033.

Kovar, J.L., T.B. Moorman, J.W. Singer., C.A. Cambardella, and M.D. Tomer. 2011. Swine manure injection with low-disturbance applicator and cover crops reduce phosphorus losses in runoff. *J. Environ. Quality* 40(2):329-336.

Kwaw-Mensah, D., and M. Al-Kaisi. 2006. Tillage and nitrogen source and rate effects on corn response in corn-soybean rotation. *Agron. J.* 98(3):507-513.

Lal, R., and B.T. Kang. 1982. Management of organic matter in soils of the tropics and sub-tropics. *Proceedings of the 11th International Society Soil Science*, Vol 3, (1982), pp. 152-178, New Delhi, India.

Lindo, P.V., R.W. Taylor, J.W. Shuford, and D.C. Adriano. 1993. Accumulation and movement of residual phosphorus in sludge-treated Decatur silty clay loam soil. *Comm. Soil Sci. Plant Analysis* 24(15-16):1805-1816.

Loecke, T.D., M. Liebman, C.A. Cambardella, and T.L. Richard. 2004. Corn response to composting and time of application of solid swine manure. *Agron. J.* 96(1):214-223.

Lory, J.A., G.W. Randall, and M.P. Russelle. 1995. Crop sequence effects on response of corn and soil inorganic nitrogen to fertilizer and manure nitrogen. *Agron. J.* 87(5):876-883.

Maguire, R.O., P.J.A. Kleinman, and D.B. Beegle. 2011. Novel manure management technologies in no-till and forage systems: Introduction to the special series. *J. Environ. Quality* 40(2):287-291.

Mallarino, A.P., and D.J. Wittry. 2010. Crop yield and soil phosphorus as affected by liquid swine manure phosphorus application using variable-rate technology. *Soil Sci. Soc. America J.* 74(6):2230-2238.

Mathers, A.C., and B.A. Stewart. 1974. Corn silage yield and soil chemical properties as affected by cattle feedlot manure. *J. Environ. Quality* 3(2):143-147.

Mehdi, B., and C.A. Madramootoo. 1999. Soil nitrate distribution under grain and silage corn using three tillage practices on a loamy sand in southwestern Quebec. *Soil Tillage Res.* 51(1-2):81-90.

Meng, L., W.Ding, and Z. Cai. 2005. Long-term application of organic manure and nitrogen fertilizer on N_2O emissions, soil quality and crop production in a sandy loam soil. *Soil Biol. Biochemistry* 37(11):2037-2045.

Nayak, A.K., R.S. Kanwar, P.N. Rekha, C.K. Hoang, and C.H. Pederson. 2009. Phosphorus leaching to subsurface drain water and soil P buildup in a long-term swine manure applied corn-soybean rotation system. *Intl. Agric. Eng. J.* 18(3-4):25-33.

NOAA (National Oceanic and Atmospheric Administration) 1996-2001. Climatological data: Annual summaries for years 1996-2001. Ashville, NC: National Oceanic and Atmospheric Administration.

Novak, J.M., D.W. Watts, P.G. Hunt, and K.C. Stone. 2000. Phosphorus movement through a coastal plain soil after a decade of intensive swine manure application*. J. Environ. Quality* 29(4):1310-1315.

Pappas, E.A., R.S. Kanwar, J.L. Baker, J.C. Lorimor, and S. Mickelson. 2008. Fecal indicator bacteria in subsurface drain water following swine manure application. *Trans. ASABE* 51(5):1567-1573.

Parkin, T.B., T.C. Kaspar, and J.W. Singer. 2006. Cover crop effects on the fate of N following soil application of swine manure. *Plant and Soil* 289(1-2):141-152.

Paschold, J.S., B.J. Wienhold, R.B. Ferguson, and D.L. McCallister. 2008. Soil nitrogen and phosphorus availability for field-applied slurry from swine fed traditional and low-phytate corn. *Soil Sci. Soc. America J.* 72(4):1096-1101.

Patni, N.K., S. Bittman, and M.C. Fortin. 1999. Effects of different rates and methods of swine and dairy cattle slurry applications on nitrate and ammonia concentrations in soil solution at different depths in forage fields. ASAE Paper No. 992103. St. Joseph MI: American Society of Agricultural Engineers.

Pote, D.H. B.A. Reed, T.C. Daniel, D.J. Nichols, P.A. Moore, Jr., D.R. Edwards, and S. Formica. 2001. Water-quality effects of infiltration rate and manure application rate for soils receiving swine manure. *J. Soil Water Conserv.* 56(1):32-37.

Powell, J.M., and J.H. Grabber. 2009. Dietary forage impacts on dairy slurry nitrogen availability to corn. *Agron. J.* 101(4):747-753.

Qian, P., and J.J. Schoenau. 2000. Effect of swine manure and urea on soil phosphorus supply to canola. *J. Plant Nutrition* 23(3):381-390.

Randall, G.W., M.A. Schmitt, and J.P. Schmidt. 1999. Corn production as affected by time and rate of manure application and nitrapyrin. *J. Prod. Agric.* 12(2):317-323.

Randall, G.W., T.K. Iragavarapu, and B.R. Bock. 1997. Nitrogen application methods and timing for corn after soybean in a ridge-tillage system. *J. Prod. Agric.* 10(2):211-212; 300-307.

Randall, G.W., and J.A. Vetsch. 2005. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by fall and spring application of nitrogen and nitrapyrin. *J. Environ. Quality* 34(2):590-597.

Randall, G.W., J.A. Vetsch, and J.R. Huffman. 2003. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by time of nitrogen application and use of nitrapyrin. *J. Environ. Quality* 32(5):1764-1772.

Reeves, D.W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil Tillage Res.* 43(1-2):131-167.

Roth, L.W., and R.H. Fox. 1990. Soil nitrate accumulations following nitrogen-fertilized corn in Pennsylvania. *J. Environ. Quality* 19(2):243-248.

Rotz, C.A., P.J.A. Kleinman, C.J. Dell, T.L. Veith, and D.B. Beegle. 2011. Environmental and economic comparisons of manure application methods in farming systems. *J. Environ. Quality* 40(2):438-448.

Sallade, Y.E., and J.T. Sims. 1997. Phosphorus transformations in the sediments of Delaware’s agricultural drainageways. I. Phosphorus forms and sorption. *J. Environ. Quality* 26(6):1571-1579.

Sanchez, P.A., C.A. Palm, L.T. Szott, E. Cuevas, and R. Lal. 1989. Organic input management in tropical agroecosystems. In *Dynamics of soil organic matter in tropical ecosystems.* Coleman D.C., J.M. Oades and G. Uehara, eds. pages 125-152. University of Hawaii, Honolulu.

SAS. 1985*. SAS User’s Guide: Statistics.*Ver. 5. Cary, NC: SAS Institute, Inc.

Sauerbeck, D.R. 1982. Influence of crop rotation, manurial treatment and soil tillage on the organic matter content of German soils, In *Proceedings of the EEC seminars*, pp. 163-179. D. Boels, D.B. Davies, A.E. Johnson (Eds.). "Soil Degradation", Baklkema, Rotterdam, The Netherlands.

Schmidt, J.P., J.A. Lamb, M.A. Schmitt, G.W. Randall, J.H. Orf, and H.T. Gollany. 2001. Soybean varietal response to liquid swine manure application. *Agron. J.* 93(2):358-363.

Schoenau, J.J., J. Charles, P. Qian, R. Wen, and G. Hultgreen. 1999. Effect of hog and cattle manure additions in the black soil zone of Saskatchewan: agronomic considerations. In *Proceedings 1999 Soil and Crops Workshop*, pages 59-70, June 22-25, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Sharpley, A.N., R.W. McDowell, and P.J.A. Kleinman. 2001. Phosphorus loss from land to water: integrating agricultural and environmental management. *Plant and Soil* 237(2):287-307.

Shigaki, F., A.N. Sharpley, and L.I. Prochnow. 2007. Rainfall intensity and phosphorus source effects on phosphorus transport in surface runoff from soil trays*. Sci. Total Environ.* 373(1):334-343.

Simard, R.R., D. Cluis, G. Gangbazo, and S. Beauchemin. 1995. Phosphorus status of forest and agricultural soils from a watershed of high animal density. *J. Environ. Quality* 24(5):1010-1017.

Sims, J.T. 1987. Agronomic evaluation of poultry manure as a nitrogen source for conventional and no-tillage corn. *Agron. J.* 79(3):563-570.

Slevinsky, L.F., and D. Small. 1997. Application of swine manure to clay soils in Manitoba. Canadian Society of Agricultural Engineers (CSAE) Paper No. 97-103, pp. 95-115, Masonville, Quebec, Canada: CSAE.

Smith, D.R., P.R. Owens, A.B. Leytem, and E.A. Warnemuende. 2007. Nutrient losses from manure and fertilizer applications as impacted by time to first runoff event. *Environ. Pollution* 147(1):131-137.

Standard Methods. 1998. *Standard Methods for the Examination of Water and Wastewater.* American Public Health Association, American Water Works Association, Water Environment Federation. Clesceri, L.S., A.E. Greenberg and A.D. Eaton, eds. 20th edition. Method 4500, pages 4-121. Washington, DC: American Public Health Association.

Sutton, A.L., D.W. Nelson, D.T. Kelly, and D.L. Hill.1986. Comparison of solid vs. liquid dairy manure applications on corn yield and soil composition. *J. Environ. Quality* 15(4):370-375.

Tabbara, H. 2003. Phosphorus loss to runoff water twenty-four hours after application of liquid swine manure or fertilizer. *J.*

Environ. Quality 32(3):1044-1052.

Thomas, G.W. 1996. Soil pH and soil acidity, pages 475-490. In *Methods of Soil Analysis*–Part 3: Chemical Methods. D.L. Sparks et al. (ed.). Soil Science Society of America Book Serial No. 5. Soil Science Society of America and American Society of Agronomy.

USDA-IFB (Iowa Farm Bureau). 1998. *Iowa Agriculture Statistics*, pp. 77, 78, 106.

USDA-NASS (National Agricultural Statistics Service). 2011. Iowa's Rank in United States Agriculture. USDA, National Agricultural Statistics Service, Iowa Field Office, Des Moines, IA: USDA

USEPA (United States Environmental Protection Agency). 2009. National Water Quality Inventory: Report to Congress, 2004 Reporting Cycle. US Environmental Protection Agency publication EPA 841-R-08-001. Washington, DC: USEPA.

USGS (US Geological Survey). 2010. The quality of our nation's water-Nutrients in the Nation's streams and groundwater, 1992-2004: US Geological Survey Circular 1350. Washington, DC: US Department of the Interior.

Vadas, P.A., R.D. Harmel, and P.J.A. Kleinman. 2007. Transformations of soil and manure phosphorus after surface application of manure to field plots. *Nutrient Cycling in Agroecosystems* 77(1):83-99.

van Es, H.M., J.M. Sogbedji, and R.R. Schindelbeck. 2006. Effect of manure application timing, crop, and soil type on nitrate leaching. *J. Environ. Quality* 35(2):670-679.

Walkley, A., and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* 37(1):29-38.

Warnemuende, E.A., R.S. Kanwar, J.L. Baker, J.C. Lorimor, S. Mickelson, and S.W. Melvin. 2001. Indicator bacteria in subsurface drain water following swine manure application. ASAE Paper No. 01-2197. St. Joseph, MI: American Society of Agricultural Engineers.

Weed, D.A.J. 1996. Nitrate and water present in and flowing from root-zone soil. *J. Environ. Quality* 25(4):709-719.

Whalen, J.K., and C. Chang. 2002. Macroaggregate characteristics in cultivated soils after 25 annual manure applications. *Soil Sci. Soc. America J.* 66(5):1637-1647.

Wienhold, B.J., and J.E. Gilley. 2010. Runoff losses of N and P after low phosphorus swine slurry application to no-tillage sorghum. *Soil Sci.* 175(5):201-206.

Wu, Z., and J.M. Powell. 2007. Dairy manure type, application rate, and frequency impact plants and soils. *Soil Sci. Soc. America J.* 71(4):1306-1313.

Xue, S.K., S. Chen, and R.E. Hermanson. 1999. Wheat straw cover for reducing ammonia and hydrogen sulfide emissions from dairy manure storage. *Trans. ASABE* 42(4):1095-1102.

Zhu, Y., and R.H. Fox. 2003. Corn-soybean rotation effects on nitrate leaching. *Agron. J.* 95(4):1028-1033.

Nomenclature

1. UAN = UAN application single rate (168 kg N ha^{-1}[150 lb N ac^{-1}])
2. RSP = Residual soil phosphorus
3. RSN = Residual soil nitrate-nitrogen
4. OM% = Percent organic matter
5. FI1 = Fall application with single application rate
6. FI2 = Fall application with double application rate (336 kg N ha^{-1}[300 lb N ac^{-1}])
7. WB1 = Winter broadcast with single application rate
8. WB2 = Winter broadcast with double application rate
9. SI1 = Spring application with single application rate
10. SI2 = Spring application with double application rate
11. SR = Average across time and method of all manure applied plots with single application rate
12. DR = Average across time and method of all manure applied plots with double application rate
13. FI = Average across rates of all manure injected plots in Fall
14. WB = Average across rates of all manure broadcast plots in Winter

15. SI = Average across rates of all manure injected in spring